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Classification and Distribution Analysis of Crop Types in Mauza Mustafabad Using GIS: Implications for Agricultural Policy and Land Use

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ABSTRACT

The study investigates agricultural patterns in Mauza Mustafabad through detailed crop classifying and analyzing using Geographic Information System (GIS) and sentinel- 2 satellite imagery. The study accesses 22 different crop categories across 7433 Khasra employing a supervised classification approach in ArcGIS to generate high-resolution agriculture map, with the primer focus on dominant agricultural landscape of different crops such as wheat, fodder and orchards. The outcome of the present research indicates that 67% of the districts have been allocated to wheat production, which has a potential yield of 258,598 metric tons. Crop density and farm size variability are reflected by the extremely well-defined geographical distribution of crops, which is correlated with the land use pattern. Further, a growing pattern in fish farming has also been addressed, which reflects variations in farming methods that drive financial incentives. The integration of classified satellite imagery with real time Khasra border system provides a reliable spatial framework for assessing land utilization and improving administrative decision making. Overall, this research shows how the integration of GIS based crop mapping and land record system can support evidence based agricultural policy, resource management and food security planning in Pakistan's precision agriculture context.

1. Introduction

Agriculture plays a pivotal role in Pakistan's economy, supporting livelihood and ensuring national food security. Accurate crop mapping and monitoring are essential for estimating yield, managing resource efficiently, and guiding evidence base agricultural policies (Rahman et al., 2020). Remote sensing and GIS techniques have emerged as effective and reliable tools for crop classification, offering comprehensive data coverage and timely acquisition (Zhai et al., 2019). Traditional agriculture databases, such as Khasra record, provide land ownership and crop related information at the parcel level but often lack spatial precision and are not regularly updated. On the other hand, satellite-based imagery (MODIS and NOAA) offers temporal coverage but suffers from moderate resolution which lead to issues such as mixed pixel and reduced accuracy form small fields (Zhong et al., 2020). Especially, a greater emphasis has been exploring the

potential of different image assessment methods and features to improve crop classification efficiency (Zhang et al., 2021). For identified the different crop varieties, the two primary classifications techniques such as the pixel-based and object-based have been extensively used (Hu et al., 2017; Hossain et al., 2019). However, pixel-based classification has been reported to be frequently utilized and considered as the strategy may be used appropriately due to its greater sensitivity and resistance to interference to differentiate various crop types. Further, in peripheral regions, data objects commonly collect identical details (Sun et al., 2019). Hence, the level of complexity in data processing and accuracy must be considered while selecting image analysis techniques (Song et al., 2018).

Recent advances in GIS and remote sensing have provided efficient, cost-effective methods for identifying, classifying and monitoring crop types. These tools allow for the integration of spectral, spatial and temporal information

to improve the accuracy of crop classification (Zhai et al., 2019; Zhang et al., 2021). Numerous studies have utilized (Bargiel et al., 2017; Cai et al., 2018; Yan et al., 2021) remote sensing-based technique for mapping of different crop varieties. In recent years, crop categorization including their spectral and spatial characteristics has gained attention especially related to their feature selection to enhance computing and mapping accuracy (Wu et al., 2017; Saini and Ghosh, 2021). Further, multiple Crop types and spectral similarity have been effectively managed by determining the vegetation indices (Zhang et al., 2014). Additionally, the integration of spectral and spatial information has been reported by various past studies for improving classification accuracy for crop types with comparable spectral characteristics (Prosek and Simova, 2019). On the other hand, land heterogeneity or complicated landscapes also have influences on classification performances. Spatial variability in topography, soil and land use patterns contributes to classification uncertainty (Samberg et al., 2016). Confrontational heterogeneity define as diversity and complexity of crop distribution within a landscape, is a critical factor affecting classification outcomes (Seidl and Golobic, 2020).

Previous studies have investigated the accuracy and variability in crop mapping and their impacts on agricultural landscapes have also been reported in past studies such as Schneider et al. (2022) investigated that crop mapping considered as significant criteria for the proportion of crops planted and index of field (Schneider, Zabel, and Mauser 2022). Although remote sensing data spans long-term data for wide locations, it is usual practice to detect crop kinds as various investigators used (Kussul et al., 2017; Momm et al., 2020; Tariq et al., 2023; Pott et al., 2022). Since various Crop types are categorized according to geographic and temporal components, the crop type to distinguish and the accessibility of previous crop classification studies. Crop kinds have been identified by spectral and temporal features since the early 1980s (Badhwar 1984). Crop-type variations are frequently shown to be greatest over certain periods (Bargiel 2017). For example, used a knowledge-based strategy in conjunction with supervised techniques like maximum likelihood and support vector machines to classify crop species in Germany. Fewer studies have looked at crop type classification in the early season (Zhang et al. 2022). Classification using the normalized difference vegetation index (NDVI) is a popular method that has been utilized by Zhao (Zhao and Qu 2024). Further, the method of machine learning, including decision tree, support vector machines, random forests and Markov models (Dabija et al. 2021), have been used in several studies to categorize different types of crops. To maximize the accessibility of

data, it is common practice to combine many sensors with varied time and spatial resolution (Omia et al. 2023). Additionally, crop kinds can be effectively distinguished by radar sensors (Bargiel 2017).

Although numerous studies and literature have applied remote sensing for crop mapping, most have focused on broad regional assessments rather than localized parcel level analysis. The absence of integration between high resolution satellite data and cadastral information restricts accurate classification of smallholder farm and localized crop diversity. To address this gap, the present research applies sentinel 2 imagery in conjunction with Khasra land records for detailed crop classification and mapping of Mauza Mustafabad. The study aims 1) classify and map multiple Crop types using high resolution sentinel 2 data. 2) Integrate GIS based land parcel boundaries for accurate spatial representation and 3) provide practical insights to support local agricultural planning, food security and sustainable land management.

2. Materials and Methods

Study Area

The Hafizabad District is situated between 73.12 E and 73.46 longitude and 31.45 and 32.20 latitude in the upper central region of the Punjab province of Pakistan with an elevation of 750 feet (Riaz et al., 2010) as shown in Figure 2. The district has a total size of 2367 square kilometers having Sugar Kalan Qadirabad Link Canal that flows from the district's eastern boundary while river Chenab is in the western boundary. Among Punjab's agricultural regions, Hafizabad is well-known for growing wheat and rice crops because of its main business of producing and processing high-quality rice, it is referred to as the "city of rice". In this district, a rain fed irrigation system is dominant with two main canal sources. Water from the river and canal irrigates half of the agricultural land with other half being watered by underground water (tub wells). Soil condition in the region is so fertile, consisting of alluvial clay loam soil having a PH of 7.83. The climate of Hafizabad varies from arid to semi-arid with hot dry summers and chilly winters. Temperature fluctuations are also seen in this district with the lowest temperature of 11°C in January and 46°C in July whereas this region receives majority of precipitation during monsoon.

Methodology and Data Collection

A mixed method strategy has been utilized in the present research to categorize and evaluate agronomic information in Mauza Mustafabad, by employing remote sensing and GIS technology. For the identification and categorization of various crop types, high-resolution satellite images served as the main source of data collection which is usually

considered as the most sophisticated image classification tool.

Image processing and categorization

To improve accuracy in classification, the satellite images were pre-processed to enhance the quality and for the remove of any distortions. Training data for the variety of crops were employed to impart the ranking algorithms for the spectral characteristics that corresponded to each crop category. For the supervised classification, maximum likelihood classifier used to base on the ground collected

signatures using ArcGIS and QGIS. This technique is efficiently performed and helps to differentiate distinct crops like wheat, fodder, vegetables, and different orchards. A total of 500 samples were collected for both classification and validation purposes, of which 350 samples were used for training the classifier across the five crop types, and the remaining 150 samples were reserved for independent validation (Overall accuracy and kappa coefficient) as shown in table 1.

Table 1: Confusion Matrix

Class type	Wheat	Fodder	Vegetables	Orchards	Pond	Total	User Accuracy (%)	Kappa Co-efficient
Wheat	26	2	1	0	1	30	85.1	0.85
Fodder	1	26	2	0	1	30	80.0	
Vegetables	1	1	27	1	0	30	92.0	
Orchards	0	0	1	28	1	30	83.4	
Pond	1	0	1	0	28	30	87.8	
Total	29	29	32	29	31	150		
Producers Accuracy (%)	89.7	89.7	84.4	96.6	90.3			
Overall Accuracy (%)					90.14			

Data collection

This investigation utilizes satellite imagery data, which has been collected from a particular satellite source such as Sentinel-2, which offers appropriate high-resolution imagery (10 meter) for in-depth agricultural studies as shown in the flow diagram in figure 1. To precisely identify the Crop types during their peak growth time, imagery from Sentinel-2 taken throughout the 2020 agricultural season.

Khasra Boundaries integration

The categorized crop data was then superimposed with the Khasra border framework, which is common in Pakistan, to match the satellite data with administrative land records by using GIS techniques. For the efficient crop allocation at the Khasra level, a comprehensive analysis was made possible by this integration, which also provides information related to farm size, land cover, and land use patterns.

Statistical Analysis

Statistical methods were chosen to evaluate the density and variety of crops across Mauza Mustafabad, along with the extent to which the geographical distribution is associated with each category of crops. For assessing the geographical patterns of agriculture in the area and to identify the dominating crops, the statistical methods made it easy to analyze the patterns. Moreover, the technique described provided a strong framework for GIS-based agricultural data analysis, as this strategy offers a reliable foundation for finding the crop patterns at such a small level.

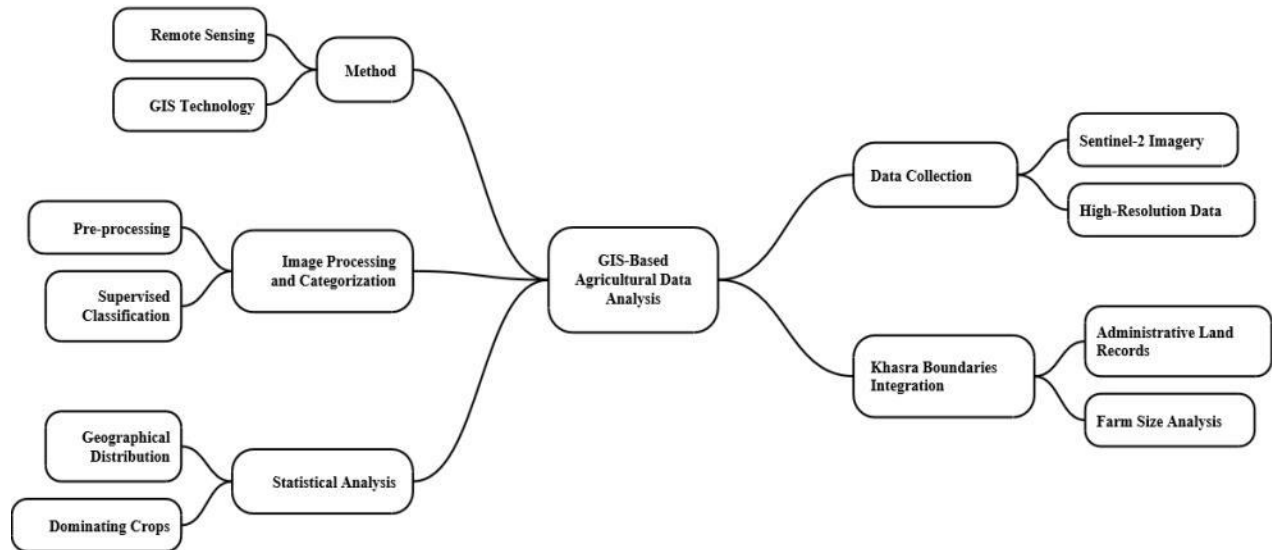


Figure 1 Workflow diagram

3. Results and Discussion

Results

Following the implementation of different techniques, the results of the study are quite varied and depict the intricate situation of facts on the ground. The number of Khasra in Mauza Mustafabad is 7433; however, 22 classes were chosen from categorized data. Khasra sizes also fluctuate, ranging from 4000 to 5000, whereas they can vary significantly in some situations as it has been demonstrated from Figure 2, a single Khasra may include one or many classes.

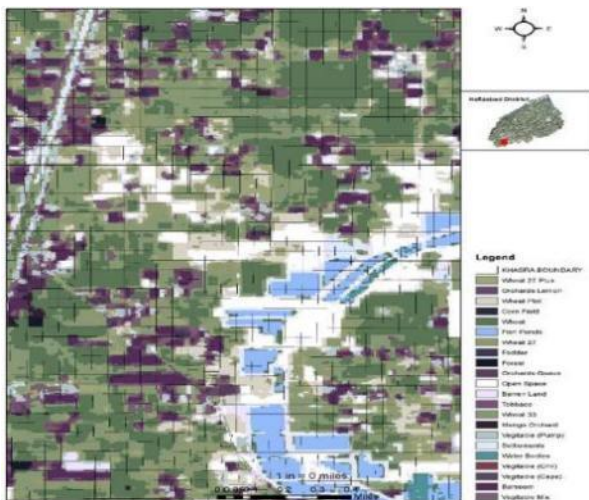


Figure 2. Demonstration of Khasra Map of Mustafabad

The details of each land use class and its corresponding area are represented within each Khasra on the map. The outcomes of this approach from the basic for subsequent conclusions, as the processes information enables decision makers and analysts to extract essential insights from the preprocesses spatial data. As illustrated in Figure 5, depicting the Hafizabad region, wheat emerges as the dominant crop class, accounting for approximately 67% of the total cultivated area. The district covers an overall area of 391,355 acres, with an estimated potential yield of 258,598 metric tons (Author, 2020). In this study, primary maps were developed at the Mauza level to provide a detailed spatial understanding of crop distribution. According to the dataset utilized, five distinct varieties of wheat were identified across the study area: (1) 1.27 mann/acre wheat, (2) 2.27+ mann/acre wheat, (3) 3.30 mann/acre wheat, (4) generic wheat, and (5) wheat plots representing areas remaining after harvest. These classifications highlight the spatial and productivity variability across the region and reinforce the precision of the approach adopted in this research.

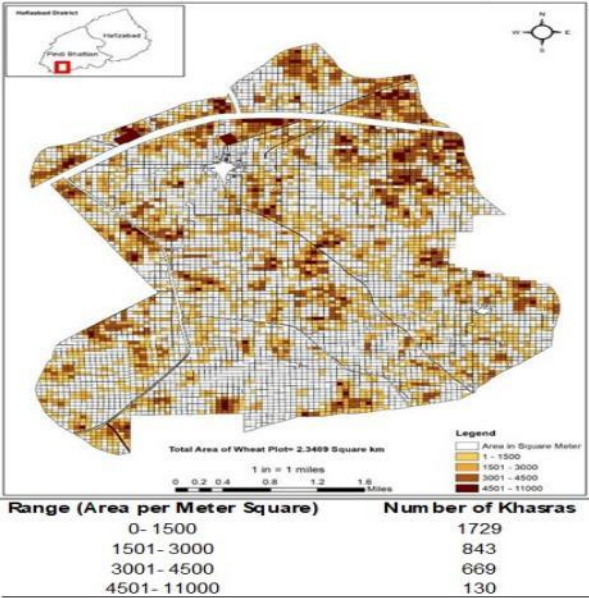


Figure 3: Khasra with area in square meters and wheat type Generic Mann per acre

The plot represents the area left fallow after harvesting. The statistical information depicted on the map indicates that most farmers cultivate wheat on plots smaller than 1,500 square meters, as illustrated in Figure 4.

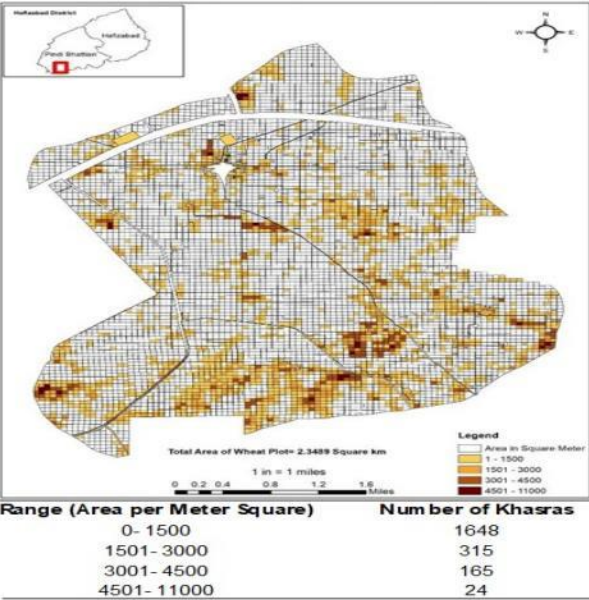


Figure 4: Khasra with area in square meters and wheat plot

A total of 7,433 Khasra were identified in the study area, among which 6,677 were cultivated with wheat. When aggregated across all classes, the following statistics represent the distribution of wheat crop holdings among farms. Approximately 88.6% of Khasra are smaller than 1,500 square meters, while 37.3% occupy areas between

1,500 and 3,000 square meters. About 20.7% of Khasra ranges from 3,000 to 4,500 square meters, and only 0.28% cover areas between 4,500 and 11,000 square meters.

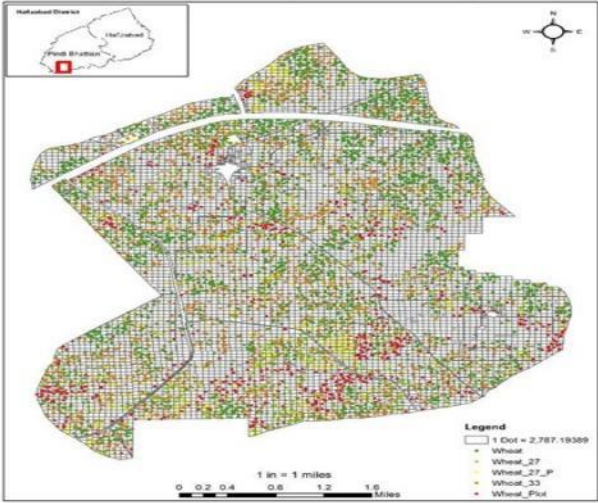


Figure 5: Khasra with area in square meters and all wheat types

Due to its year-round cultivation cycle and extensive planting coverage, fodder emerged as the second most significant crop. As illustrated in Figure 5, two major fodder types—fodder and Berseem were identified, collectively covering 1,682 Khasra. Among these, 1,258 Khasra occupy areas smaller than 1,500 square meters, while 424 Khasra exceed 1,500 square meters.

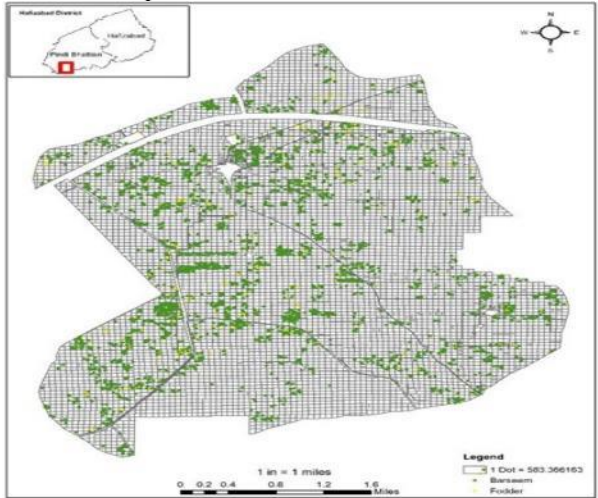


Figure 6: Khasra fodder crops

In Punjab, Pakistan, vegetables represent another major crop category. Although vegetable farms generally cover smaller areas compared to other crops, they are present in nearly every Khasra. In this study, researchers refined the classification scheme by excluding vegetable classes from

certain analyses, as their small plot sizes can introduce significant errors when the number of training samples is limited or when classification algorithms are not optimally calibrated.

In Hafizabad, four major types of vegetables were identified, as illustrated in Figure 6. Among these, 4,013 Khasra cover areas smaller than 1,500 square meters, while 516 Khasra exceed 1,500 square meters. This distribution highlights the predominance of small-scale vegetable cultivation across the district.

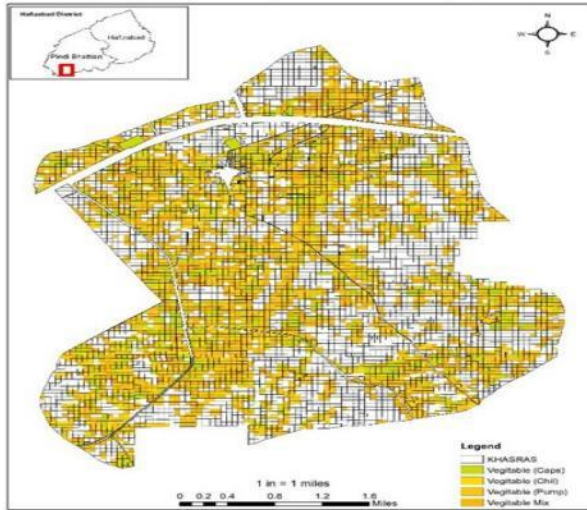


Figure 7: Khasra with all varieties of vegetable crops

Compared to vegetable crops, orchard farms are also present in the study area, though they exhibit relatively low spatial density and complex classification characteristics. In this research, orchards were categorized into three primary types of mangoes, guava, and lemon as illustrated in Figure 8. The spatial distribution indicates that 1,999 Khasra cover areas smaller than 1,500 square meters, while 69 Khasra exceed 1,500 square meters. This pattern reflects the limited but diverse presence of orchard cultivation within the region.

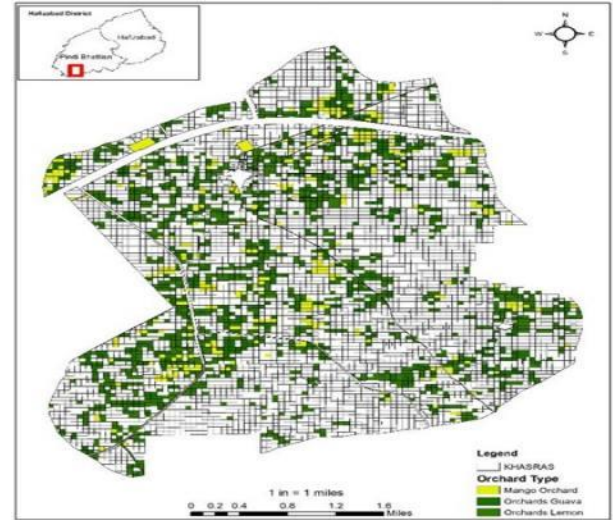


Figure 8: Khasra with different types of orchards

As previously stated, the research findings demonstrated an overall accuracy of approximately 90%, closely reflecting the actual ground conditions (Author, 2020). It was further observed that, depending on the farm size and Khasra boundaries, a single Khasra may encompass one or multiple land-use classes, as illustrated in Figures 9 and 10.

In the second part of the present research, the advantages of fish farming have been evaluated as the government has been promoting fish farming for the past two years because it yields a high profit margin. It has also been observed that those farms that are located close to the river turn their farms into fish farms. However, in Mauza Mustafabad, there are around 240 ponds and fish farms are identified as shown in figure 10.



Figure 9: Khasra having 1 to 3 crops

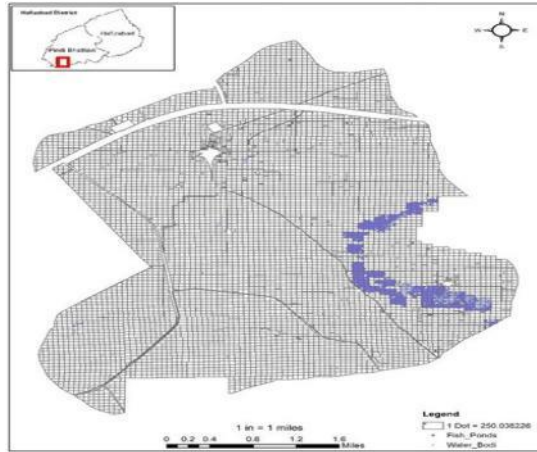


Figure 10: Khasra major water bodies including fish farm and ponds

A total of 247 Khasra were identified as containing fish farms and water bodies. Specifically, 240 Khasra include fishponds, while 70 Khasra contain natural or artificial water bodies. When combined, the total number of water features, including fishponds, amounts to 310. Furthermore, 63 Khasra were found to contain both fishponds and water bodies, indicating areas where aquaculture and surface water resources coexist.

Discussion

The population growth, high demands of crop and global warming are those worldwide issues for which monitoring of agricultural land is highly significant. According to Foley et al. (2005), pasture and agricultural land already occupy approximately 38% of the Earth's Land surface. yet the expansion of farmland is often associated with detrimental ecological effects, including deforestation and biodiversity loss, particularly in vulnerable ecosystems (Eitelberg et al., 2015).

To distinguish different varieties of crops, the current research utilizes a variety of classification algorithms that are based on GIS and remote sensing techniques. The research findings suggested that the input data, method selection and spatial-temporal resolution affect the model accuracy, especially when compared with the unsupervised algorithms, supervised classification techniques demonstrate superior accuracy. The comparable spectral signatures, when the growth stage of crops overlapped, most misclassification errors happened in crops.

Analysis of spatial patterns revealed that crop distribution is shaped by both environmental and socio-economic factors. Wheat and maize dominate arid and semi-arid regions due to their drought resistance and adaptability to limited water availability, reflecting both ecological constraints and farmers' strategic choices to optimize yield. In contrast,

vegetables and orchards are cultivated on smaller, fragmented plots, often near water sources, suggesting a preference for high-value, labor-intensive crops. The prevalence of small- and medium-sized Khasra underscores land fragmentation trends, which can limit mechanization and efficiency, while also influencing water use, as dispersed plots require individualized irrigation management. By the distribution analysis, different spatial trends that are influenced by soil type, climate, and irrigation availability were examined, whereas those crops that are drought-resisted should be more prevalent in arid regions, such as wheat and maize. The distribution and classification of crops are significantly influenced by different environmental factors such as rainfall patterns, temperature changes, and moisture content of the soil as the alteration in these trends may have a direct influence on suturing sustainable crops, necessitating the use of different adaptive measures.

Overall, the study highlights the complex interactions between crop choice, landholding patterns, and environmental conditions. Sustainable agricultural planning must therefore integrate adaptive crop selection, land management strategies, and efficient water resource allocation to enhance productivity while minimizing ecological impacts.

4. Conclusion

This study employs advanced GIS and remote sensing techniques to map and analyze crop distribution in Mauza Mustafabad, revealing that wheat dominates 67% of the cultivated area alongside significant vegetable, fodder, and orchard cultivation. By integrating high-resolution satellite imagery with the Khasra boundary system, the research provides detailed, micro-level insights into land use and crop diversity. The findings highlight evolving agricultural trends, including shifts toward aquaculture, and offer valuable guidance for policymakers and agricultural managers to enhance productivity through GIS-based decision-support tools. However, late-stage data may miss early crop events, be affected by cloud cover, and create spectral mixing in intercropped or harvested fields, representing important limitations of the study.

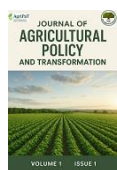
Future research could focus on using deep learning models for crop mapping and classification. Methods like Convolutional Neural Networks (CNNs) can automatically identify important patterns from high-resolution satellite images, improving accuracy and reducing manual work. Combining deep learning with time-series satellite data and ground-truth information could help detect crops earlier, estimate yields more accurately, and support better decision-making in agriculture.

Based on the findings of this study, several key policy implications can guide sustainable and productive agriculture in Mauza Mustafabad. Policies should promote crop diversity to ensure biodiversity and food security while providing incentives for sustainable farming practices that optimize long-term yields, such as the cultivation of high-performing wheat varieties identified in this study. Efficient allocation of resources, including water and agricultural support, should account for regional crop patterns, particularly in areas with intensive cultivation or aquaculture. The adoption of remote sensing and GIS technologies should be encouraged to enable precision agriculture, reduce waste, and support data-driven crop management, including the development of GIS-based applications and predictive analytics for pest management. Finally, community engagement is essential, with outreach programs educating farmers about modern technologies and decision-making based on data, while forums that bring together farmers, technicians, and policymakers can facilitate the integration of traditional practices with contemporary agricultural techniques. Collectively, these strategies aim to foster a technologically advanced, sustainable, and productive agricultural sector in the region.

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Climate Change Adaptation and Farmers' Resilience in Pakistan

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ARTICLE INFO	ABSTRACT
Keywords: Climate change Climate change resilience Awareness Adaptive capacity Received: 16 October 2025 Received in revised form: 06 November 2025 Accepted: 07 November 2025 Available online: 13 November 2025	To avoid the hazardous impact of climate change in agriculture sector particularly small farm holder, the adaptation to climate change requires time. The degree of adaptive responses has been slow among the farmers since they have low adaptive capacities in developing countries like Pakistan owing to their ignorance. Thus, the purpose of study is to determine the awareness degree of the farmers, to examine the factors that impact the adaptive to climate change. Moreover, the type of the study is cross-sectional and 280 farmers data is gathered with the assistance of well-developed questionnaire on the basis of former researches. Multistage method is applied in collecting data in district Vehari. To carry out the data analysis, binary logit model and odd ration model is used in finding out the factors contributing to the adaptive capacity of climate change. In the foundation of the analysis of data presented in this paper, it is stated that climate adaptation to the climate change is talkative with the growth of information resources: technology can make agriculture too efficient and the climate change awareness. The facts presented in the current study are borne out by facts that indicate the need to award credits and finance long term, agricultural technologies that will hasten the ACC and in the short-term information on climate should be disseminated among the agricultural circles.

1. Introduction

Climate change has become one of the most burning issues in the world in the 21st century with agriculture being the most susceptible one, especially in the developing nations like Pakistan. Pakistan was one of the top 10 nations which were the most affected by extreme weather events in the previous 20 years. Floods, droughts, heat waves, and inconsistent rain patterns have had a critical effect on the agricultural productivity and livelihoods in the country (Adil et al., 2025).

Pakistan has a GDP of approximately 23.54 that is contributed by agriculture and around 37 percent of the labor force is employed by agriculture (GOP, 2025). The industry however is highly climate-vulcanized since a majority of the arable land relies on the Indus Basin irrigation which is itself facing the risk of glacial melt, water deficiency and unreliable monsoon seasons. Research estimates the percentage of climate change decreases in major crop yields

in Pakistan of 8-10 percent in wheat and 15-20 percent in rice without proper adaptive actions by 2050 (FAO, 2022).

The farmers are the first line of climate change victimization, and the way they can adapt to this depends on their climate change awareness and adaptive capacity (AC). Adaptive capacity defines the human, financial, physical, social and natural resources that help farmers to cope with changes in climate. However, in Pakistan, the smallholder farmers who comprise about 80 percent of the farming society frequently experience shortage of resource, inability to access technology, low quality of the extension, and lack of institutional support.

Awareness of climate change is also of great importance. In a national survey of Ali and Erenstein (2017), fifty percent of farmers in Punjab had even heard of climate change, and among those who have, only 36 percent could link climate change to making a modification to the way they live their agricultural lives. The implication of such poor knowledge is that it takes a long time before there is awareness about

how to adapt to the changes, such as the planting date, change of crops, use of water, and diversification of crops and livestock.

This study is therefore highly important as it seeks to examine how farmers awareness and adaptive capability can help Pakistan to adapt to climate change. Understanding these factors better can not only provide insights into what prevents adaptation, but it can also inform policy makers of the need to initiate certain intervention such as improving agricultural extension, spreading climate information services and availability to financial and technological opportunities. These are vital projects that will contribute in safeguarding Pakistan food security and offer sustainability of Pakistan agricultural industry in the long term in response to uncertainty in climate. Therefore, the study has objectives -The aim of the study is 1) To determine the extent of the climate change awareness of the farmers about adaptation 2) To determine the factors that may affect the adaptation to climate change in South Punjab.

Literature review and conceptual framework

This part of study explained the dependent and independent variables in detail and also elaborated the previous studies

Adaptation to climate change

In agricultural practice, farmers are using various climate change adaptations strategies to deal with climatic risks. These encompass changing crop Variety (CCV) e.g. adoption of stress-resistant cultivars; changing the date of planting (CPD); and changing the type of crop (CTC) i.e. farmers switching to other types of crops when the original ones become very susceptible to the effects of the climate (Zenda & Rudolph, 2024). The use of diversification strategies (DSs) (intercropping, livestock rearing, planting various types and varieties of crops, etc.) is also a common practice in order to minimize both climatic and economic risks (Danson-Abbeam et al., 2021). Moreover, soil conservation (SC) and water conservation (WC), are quite frequent practices associated with erratic rainfall and increasing temperatures (Marie et al., 2020; Sinore and Wang, 2024). These ACC practices combined will reduce risks and alleviate the intensity of climate change effects (Ahmad et al., 2024).

Climate change awareness

Communication, knowledge, education, and information sharing play a significant role in the transfer of the farmers to effective adaptation to climatic changes strategies (ACC) with limited resources (Zorrilla-Miras et al., 2024). The availability of adequate information puts the smallholder

farmers in a better position to address the challenges of adaptation despite having limited resources (Eise and Rawat, 2021; FAO, 2019). In one of the studies, Belay et al. (2017) demonstrated that climate information plays a paramount role in the adaptation of farmers in Ethiopia, and Piya et al. (2013) emphasized that it is a paramount role in the practices of adoption among Nepalese farmers. It has been noted that the application of climate information is a key determinant of adaptation based on an enormous body of research (Ali et al., 2021; Ali and Rose, 2021; Khanal and Wilson, 2019; Mehmood et al., 2021).

Farmers (CCK) awareness of climate change is typically affected by previous experience of climate variability, personal perceptions, social values and personal opinions, but tends to be informed by little scientific evidence (Thottadi & Singh, 2024). This subjective interpretation may lead to critical gaps of knowledge that must be addressed by scientific facts and evidence. Such subjective interpretation could result in critical knowledge gaps that have to be filled by scientific facts and evidence (Appiah et al., 2025; Prajapati et al., 2025). Nevertheless, there is some evidence, which indicates that not all farmers have enough CCK, and it restricts its potential in modification strategies (Ali et al., 2021). This ambiguous evidence points to the necessity of legitimizing the knowledge of farmers by using a scientific viewpoint (Mao et al., 2024). Therefore, the study of the role of CCK in ACC strategies in rural Punjab needs to be continued to advance further.

The availability of climate change information is usually kept as a control variable when analyzing factors that influence adaptation (Zagre et al., 2024). It is conceptualized in most instances to be the simple acquisition of information. In filling this gap, the current study expands the conceptualization of information by investigating how education (volume), joining farmer organizations (type of channel), and access to extension services (frequency) influences the way adaptation measures are formed. Earlier researchers have indicated that education has a significant impact on adaptation strategies (Chaudhary et al., 2025), whereas farmer-to-farmer interactions via organizations play a significant role in adaptation plans implementation (Koch et al., 2025; Prajapati et al., 2025).

Climate change adaptive capacity

Adaptive capacity (AC) is the potential of individuals, households or systems to react successfully to climate variability and extremes by diminishing potential risks, using arising opportunities, and managing environmental challenges. Researchers emphasize that the adaptive ability

of households is one of the major factors that dictate the success of climate change adaptation (Chishiba, 2024; Wright et al., 2024; Hossain et al., 2019). The adaptive ability involves physical and non-physical resources. It is not new that the resources at the local context, particularly livelihood assets play a critical role in increasing AC.

Furthermore, When it comes to the sphere of agricultural systems, farmer competence and skills are critical in determining their awareness and understanding of the uncertainty of climate change, thus their ability to counteract them (Jatav et al., 2024). Prior investigations have indicated that factors such as educational attainment agricultural experience, the composition of household size (Chatsiwa, 2024; Chaudhary et al., 2025; Arshad et al., 2018), and the availability of labor resources (Byrne, 2014) constitute essential components of human capital that bolster farmers' adaptive capacity (AC) and, as a result, their adaptive capacity to climate change (ACC). Likewise, the presence of social capital is instrumental in fortifying community resilience (Suhaeb et al., 2024).

On the base of above explanation, current study selected the Adaptation of climate change strategies as dependent variables and climate change awareness and climate change adaptive capacity as independent variable.

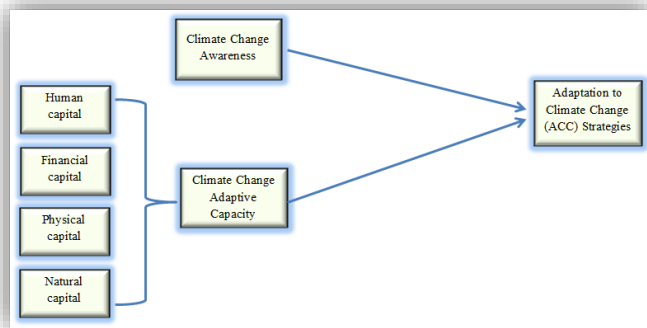


Figure 1 Conceptual framework

In this figure 1 the climate change capacity is measure with the help of human capital, financial capital and physical capital and natural capital.

3. Materials and Methods

Sample size and data collection

This study adopted a quantitative research design. Primary data were collected from the Punjab province, the most densely populated region of Pakistan, using a multi-stage random sampling method. The survey gathered information on farmers' knowledge of climate change, focusing on

temperature, rainfall, and seasonal as well as weather patterns. Questions related to sea level rise were excluded since Punjab is not a coastal region. To overcome communication barriers, the questionnaire was translated into Urdu and Punjabi. Farmers were assured of anonymity, and informed that the data would be used solely for research purposes. Trained monitors were engaged to conduct the field survey, ensuring consistency in data collection. In total, responses were collected from 280 farmers between August and September 2024, coinciding with the wheat harvesting and rice sowing seasons, when farmers are most actively involved in agricultural activities. Further, this study has applied binary logit model for the data analysis by using STATA.

Measurement of variable

In this study following table explains the nature of variables, proxies and measurements scales.

Table 1: Explanation of variables and measurement

Variable	Dimension	Measurement / Coding
Adaptation to Climate Change (ACC) Strategies	CCV, CCT, CPD, SC, WC, DSs	(1=Adopted, 0=Not adopted)
Climate Change Awareness (CCA)	Knowledge about climate change	1 if knowledge present; 0 otherwise
Human Capital	Age, Education, Family Size, Labor	Years; Schooling; Household size; No. of workers
Financial Capital	Agricultural Credit, Marketing Access, Off-Farm Income	1=Yes, 0=No
Physical Capital	Tube Well, Transport, Sowing & Harvesting Tools	1=Owned, 0=Not owned
Natural Capital	Landholding, Tenancy Status,	Acres; 1=Owner, 0=Tenant;

Note: Change Crop Variety (CCV), Change Crop Type (CCT), Change Planting Date (CPD), Soil Conservation (SC), Water Conservation (WC), Diversification Strategies (DSs), Climate Change Awareness (CCA)

This table explains that dimension of Adaptation to Climate Change (ACC) Strategies which is dependent variables, while Climate Change Awareness (CCA) and farmer's adoptive capacity are independent variable. The farmer's adoptive capacity is measure with human capital, physical capital, financial capital and natural capital.

Empirical model

Current study has applied binary logit model to elaborate the variable effecting the Adaptation to Climate Change (ACC) Strategies. Following equation is used for the logit model: -

$$\ln\left(\frac{L_i}{1-L_i}\right) = \alpha + \sum_{i=1}^{18} \beta_i X_i + \varepsilon \quad (1)$$

Where $\ln\left(\frac{L_i}{1-L_i}\right)$ represents the logit for the farmers' ACC strategies (e.g., L_i is the probability of the farmers adopting the i ACC strategy, while $1 - L_i$ is the probability of the farmers not adopting the particular strategy).

The set of independent variables and their short forms, measurements, means, standard deviations, and minimum and maximum values are provided in Table 3.

4. Results and Discussion

Results

To calculate the statistical software, the current study used STATA. Logit regression models of the chosen strategies of adaptation.

Descriptive statistics

The descriptive statistics demonstrate the significant attributes of the farmers, their resources and the adaptation strategies they adopt to address climate change. These findings indicate that most farmers are already adapting with 64% switching to different types of crop varieties, 54% switching to different types of crops, and 49% changing the

The econometric equations of this study is following

$$\begin{aligned} ACC = & \alpha + \beta_1 CCA_1 + \beta_2 age_2 + \beta_3 edu_3 + \beta_4 FS_4 \\ & + \beta_5 labor_5 + \beta_6 AC_6 + \beta_7 MP_7 \\ & + \beta_8 OFI_8 + \beta_9 TW_9 + \beta_{10} TT_{10} \\ & + \beta_{11} ST_{11} + \beta_{12} HT_{12} + \beta_{13} land_{13} \\ & + \beta_{14} TS_{14} + \varepsilon_t \quad (2) \end{aligned}$$

$$\begin{aligned} \ln\left(\frac{L_i}{1-L_i}\right) = & \alpha + \beta_1 CCA_1 + \beta_2 age_2 + \beta_3 edu_3 \\ & + \beta_4 FS_4 + \beta_5 labor_5 + \beta_6 AC_6 + \beta_7 MP_7 \\ & + \beta_8 OFI_8 + \beta_9 TW_9 + \beta_{10} TT_{10} \\ & + \beta_{11} ST_{11} + \beta_{12} HT_{12} + \beta_{13} land_{13} \\ & + \beta_{14} TS_{14} + \varepsilon_t \quad (2') \end{aligned}$$

Furthermore, this study also analyzed the odds ratio. For this purpose, following equation is used.

$$\frac{p_i}{1-p_i} = \exp\left(\beta_0 + \sum_{i=1}^{18} \beta_i X_i\right) \quad (3)$$

planting dates. Fifty-five percent and 48% of farmers respectively had soil and water conservation techniques and 59 percent diversified by means of intercropping, livestock or alternative means. Climate change awareness was also high with 75% of the farmers expressing that they were aware of issues related to climate, which means that the climate information is quite prevalent in the area. Regarding human capital, the mean age of farmers was 30 years with the age of farm workers spanning between 17 and 80 years, indicating that there were young and experienced farmers. Education levels were low with an average of seven years of schooling and family sizes were relatively large with an average of 9 members and 3 contributing laborers.

In terms of financial capital, access to agricultural credit and access to markets stood at 49 percent and 44 percent respectively, off-farm income was reported by only 31 percent, indicating lack of financial diversification. There was a relatively high level of physical capital with 68 percent of the farmers having tube wells, 69 percent having tools of transport and more than half of the farmers having sowing and harvesting tools and harvesting tools. Natural capital showed great inequity, with the average landholding of 15.6 acres with a variation of 1 to 100 acres, showing there was

an unequal distribution of land. In addition to this, land tenure was important as only 44 percent of farmers were landowners and the remainder were tenants; therefore, land tenure facilitated the adaptation decisions. In general, the results indicate that farmers are implementing various adaptation strategies and have average access to physical resources, but lack of education and financial assistance and unequal land distribution remains a challenge that limits their adaptive capacity.

Table 2: Determinant of the ACC strategies

Variables	CCV	CCT	CPD	SC	WC	DS
Climate Change Awareness	0.9187 (0.3520) ***	0.9248 (0.3651) **	1.3412 (0.4225) ***	1.1086 (0.3998) ***	-1.0854 (0.4030) ***	0.8539 (0.4201) **
Human Capital						
Age	0.0527 (0.0184) ***	0.0375 (0.0121) ***	0.0971 (0.0111) ***	0.0079 (0.0126)	0.0588 (0.0096) ***	0.0114 (0.0118)
Education	0.1614 (0.0371) ***	0.1086 (0.0388) ***	0.0553 (0.0378)	0.0415 (0.0416)	0.0852 (0.0372) ***	-0.0295 (0.0415)
Family size	0.0352 (0.0398)	0.0034 (0.0381)	0.0877 (0.0382) **	0.0221 (0.0445)	0.0081 (0.0487)	0.0998 (0.0465) **
Labor	0.0738 (0.0934)	0.1031 (0.0847)	0.0742 (0.0725)	-0.2762 (0.1052) **	0.2701 (0.0838) ***	0.0012 (0.0781)
Financial Capital						
Agricultural credit	1.1743 (0.3356) ***	0.6915 (0.3167) **	-0.2103 (0.3375)	0.7942 (0.3741) **	1.4261 (0.3085) ***	0.5169 (0.3949)
Marketing access	1.0824 (0.3664) ***	0.5032 (0.3609)	1.3241 (0.3267) ***	0.4263 (0.3702)	-0.4519 (0.3640)	0.2084 (0.3699)
Off-farm income	0.0961 (0.4029)	0.4525 (0.3762)	-0.1218 (0.3271)	0.9726 (0.3758) ***	0.0551 (0.3215)	1.6732 (0.3625) ***
Physical Capital						
Tube well	-0.3587 (0.4079)	-0.4059 (0.4046)	-0.4821 (0.4041)	0.4051 (0.3958)	0.9368 (0.3842) **	-0.2968 (0.4583)
Transport tools	1.0498 (0.4337) **	-0.0764 (0.4540)	0.4221 (0.3975)	-0.1075 (0.4971)	0.1925 (0.3774)	1.1393 (0.4741) **
Sowing tools	-0.4821 (0.4438)	0.5126 (0.3801)	0.1812 (0.3792)	0.8195 (0.3586) **	-0.0518 (0.3643)	0.6291 (0.3529) ***
Harvesting tools	-0.4256 (0.3602)	0.3415 (0.3611)	0.0192 (0.3203)	0.9517 (0.3621) ***	0.4425 (0.3268)	0.1502 (0.3972)

Natural Capital						
Landholding	-0.0023 (0.0094)	-0.0015 (0.0083)	-0.0015 (0.0083)	0.0341 (0.0161) **	-0.0022 (0.0098)	0.0169 (0.0099) ***
Tenancy status	0.3082 (0.3985)	0.6305 (0.3759) ***	-0.4109 (0.3345)	-0.6518 (0.4181)	0.2292 (0.3457)	-0.3097 (0.3958)
Model Fit						
Wald χ^2	129.84	114.27	98.32	106.81	91.54	110.29
Prob > χ^2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pseudo R²	0.3572	0.3875	0.3591	0.4583	0.3172	0.4115

The results of this research point to the fact that the response of farmers to climate change depends greatly on the interplay of socioeconomic, institutional, and resources factors. Climate change awareness turned out to be a determinant factor, with a significant probability of implementing the adoption of a strategy of changing crop varieties, changing crop type, changing the planting date, and conserving the soil (Muchacka & Miarka-Żukowska, 2024; Tayan et al., 2024). Interestingly, awareness was observed to have a negative impact on water conservation behavior, which is a possible indication that even with awareness, structural and resource limitation or constraints suppress the application of water-saving methods in practice. There was also a significant influence on socioeconomic variables like age, education, family size and off-farm income. With regard to the adoption of modern practices, especially those related to the crop, older farmers and those who were more educated were more inclined to adopt modern practices, and it seems that experience and knowledge increase adaptive decision-making (Mastrorillo et al., 2024). The care of more laborers in bigger households supported crop diversification and income diversification

policies whereas the off-farm income greatly supported the soil conservation and diversification policies.

The Wald χ^2 values across all six adaptation models (ranging from 91.54 to 129.84) are statistically significant at the 1% level (Prob > χ^2 = 0.0000). This confirms that, overall, the explanatory variables included in the models jointly influence farmers' adaptation decisions, and the models are a good fit for the data.

The Pseudo R² values range between 0.3172 and 0.4583, indicating that the explanatory variables account for approximately 32% to 46% of the variation in the adoption of different adaptation strategies. While these values are modest, they are considered reasonable for behavioral and social science models where individual decision-making is influenced by multiple unobservable factors. Among the models, soil conservation (Pseudo R² = 0.4583) shows the strongest explanatory power, followed by diversification strategies (Pseudo R² = 0.4115), suggesting that the included variables are particularly effective in explaining these two adaptation practices.

Table 3: Odd ratio of selected strategies

Variables	CCV	CCT	CPD	SC	WC	DS
Climate Change Awareness	2.53***	2.55**	3.92***	3.09***	0.33***	2.39**
Age	1.06***	1.04***	1.10***	1.01	1.06***	1.01
Education	1.18***	1.12***	1.06	1.04	1.09***	0.97
Family size	1.04	1.00	1.09**	1.02	1.01	1.11**
Labor	1.08	1.11	1.08	0.75**	1.32***	1.00
Agricultural credit	3.32***	2.02**	0.81	2.25**	4.24***	1.69
Marketing access	3.02***	1.67	3.85***	1.54	0.63	1.24
Off-farm income	1.10	1.59	0.88	2.68***	1.06	5.48***
Tube well	0.69	0.66	0.61	1.51	2.59**	0.74
Transport tools	2.91**	0.93	1.54	0.90	1.22	3.20**
Sowing tools	0.61	1.68	1.20	2.31**	0.95	1.89***
Harvesting tools	0.65	1.41	1.02	2.62***	1.57	1.17
Landholding	1.00	1.00	1.00	1.04**	1.00	1.02***
Tenancy status	1.38	1.91***	0.66	0.51	1.26	0.73

Such findings suggest that the capacity at the household level, both human and financial resources continue to be central to development of resilience in relation to climate change. Agricultural credit contributed significantly to adopting crop technology and conservation practices a sign that the value of financial support in addressing climate-related risks is significant. Equally, the access to the market influenced favorably the diversification strategies, and the role of linkages to value chains in the development of adaptation. The farmers that could get access to tools and tube wells were more likely to adopt conservation measures that show that availability of resources directly positively impacts adaptive capacity.

Discussion

In this current study, there are climate change awareness and adaptive capacity are the independent variables. The results indicate that climate change awareness (CCA) plays a central role in determining how the farmers respond to the

climate change. Farmers who are more climate-aware will be in a better position to implement diverse practices such as altering crop variety (CCV), alteration of crop type (CCT), planting date (CDP), soil conservation (SC) and diversification strategies (DSs). This means that adaptive capacity is extremely facilitator of awareness and knowledge. Further, this study explains that the Availability of these physical resources increases the capacity of the farmers to embrace new practices successfully. As an illustration, transport and irrigation systems facilitate the implementation of changes in crop preferences or in planting times, contemporary tools facilitate the practice of soil and water conservation. The results are a line with (Appiah et al., 2025; Panja et al., 2024; Prajapati et al., 2025; Thottadi & Singh, 2024)

Additionally, if it is considered the natural capital, tenancy and landholding have ambivalent impacts. The overall impact of landholding is not so strong, but it has a positive impact on soil conservation and diversification policies. The

status of tenancy on the other hand has a big influence on the adaptation decisions: tenants would be more willing to change the type of crop (CCT), whereas landowners would be more willing to change the soil conservation practices. This explains why access and ownership of land defines the kind of strategies that farmers seek (Mehmood et al., 2018; Rabbany et al., 2021; Jounior et al., 2021).

Age, education, family size, and labor are some of the human capitals that exhibit high and positive effects on the strategies such as CCV, CCT, CPD, SC, and DSs. Farmers who are educated and those who have family support can take more adequate measures regarding adaptation. Yet, the most interesting observation is that labor availability is negatively associated with soil conservation, which may be due to the fact that households that possess more labor tend to prefer short-term income-generating activities to long-term soil management. The results are a line with (Chishiba, 2024; Koch et al., 2025; Prajapati et al., 2025; Wright et al., 2024)

Lastly, financial capital is also identified to be a key facilitator of adaptation. Agricultural credit facilitates farmers to use the strategies, including CCV, CCT, SC and water conservation (WC). Market access encourages farmers to adopt new crop types and changes planting dates whereas off-farm earnings are a major factor in diversification. Finance, therefore, gives the farmers the freedom and assurance to invest in climate resilient practices and lessen the reliance on a single source of income (Hussain et al., 2022).

5. Conclusion

In conclusion, the findings of this study highlight that climate change awareness and adaptive capacity are crucial determinants of farmers' climate adaptation behavior. Farmers with higher awareness and strong adaptive capacity are more likely to adopt multiple climate-resilient strategies such as crop variety and type adjustments, planting date alteration, soil conservation, and diversification. Access to physical resources, including irrigation, transportation, and modern agricultural tools, further strengthens their ability to implement these practices effectively.

The study also underscores the role of natural capital, particularly landholding and tenancy status, in shaping adaptation choices. While landholding has a modest effect overall, it supports soil conservation and diversification efforts, whereas tenancy encourages crop-type changes. Similarly, human capital factors especially education, age, family size, and labor availability significantly influence

adoption behavior. However, the negative association between labor availability and soil conservation suggests a preference for short-term economic gains over long-term land sustainability in households with more labor resources.

Finally, financial capital emerges as a key enabler, empowering farmers through credit access, market linkages, and off-farm income opportunities, which collectively support the adoption of climate-resilient strategies. Overall, strengthening awareness, improving access to resources, enhancing education, and promoting financial support systems are essential pathways to building resilient farming systems capable of confronting climate change challenges effectively.

6. Limitations and recommendations for future studies

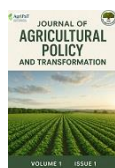
Despite the fact that this research gives significant results about the knowledge of farmers about climate change and their adaptation strategies, it is not without its limitations. First, the research was confined to the Punjab province of Pakistan, which limits the applicability of the results to other areas with other characteristics in terms of socio-economic, cultural, and environmental factors. Second, the study utilized self-reported data that is also prone to biases in terms of erroneous recall or social response desirability. Third, the research was mainly based on quantitative research and lacked inclusion of qualitative data which would have given further insights into how the farmers thought and how they made their decisions. Last but not the least is the cross-sectional design of the study which hinders the possibility of adopting long term changes in adaptive behaviour and climate changes influence among farmers. Research in the future may also broaden the geographical area to other provinces of Pakistan and comparisons across countries (such as South Asia) to increase the external validity of the results. To identify subtle views and cultural drivers to adaptation, including qualitative approaches, focus group discussions or in-depth interviews would be helpful. It is also suggested to use longitudinal research designs to monitor the changes in the adaptive capacity and behavior. Additionally, further studies can be done on how policy interventions, institutional support and technological innovations influence adaptive strategies of farmers. In the end this study also suggest that comparative analysis is also needed to find out the outcome form the adaptation from different area and farmer.

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Determinants of Solar-Powered Irrigation System Adoption Among Rice Farmers in Hafizabad, Pakistan

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ABSTRACT

The growing energy crisis and worsening water scarcity in Pakistan have intensified the need for renewable energy solutions in agriculture. Among these, solar-powered irrigation systems (SPIS) have emerged as a sustainable and economically viable alternative to conventional irrigation methods, particularly in regions cultivating water-intensive crops such as rice. This study examines the socio-economic, technical, institutional, and perceptual factors influencing the adoption of SPIS among rice growers in the Hafizabad District of Punjab, Pakistan.

Data were collected through a structured questionnaire administered to 200 randomly selected rice farmers. Descriptive statistics, correlation analysis, and binary logistic regression were employed to determine the relationship between farmer characteristics and the likelihood of adopting SPIS. The results revealed that education level, farm income, landholding size, access to credit, awareness, perceived economic benefits, and extension contact significantly affected adoption decisions. However, widespread diffusion of SPIS remains constrained by high initial investment costs, inadequate institutional support, and limited policy incentives.

The findings underscore the need for targeted policy interventions, including financial subsidies or credit facilities, technical training, awareness programs, and stronger institutional frameworks to accelerate the adoption of SPIS. Promoting such renewable technologies can enhance energy security, reduce production costs, and foster sustainable agricultural growth in Pakistan.

1. Introduction

Pakistan has traditionally relied on agriculture as it has been the primary contributor to the national GDP approximately one-fifth of the population and has been supporting more than one-third of the population. Nevertheless, the industry is struggling with some dire issues, namely, water scarcity, the increased energy prices, and environmental deterioration, compounded by the effects of climate change and the increased population rate. Water and energy management is essential to sustain a high level of land irrigation in Pakistan, which covers over 90 percent of the country (Pakistan Economic Survey, 2023).

Rice is a key crop and especially in Punjab Province; Hafizabad District has been major producer of rice in the country. The Basmati rice grown in Hafizabad needs regular

and inexpensive irrigation, but the growers have to deal with unstable diesel prices and unreliable electricity supply, which results in the production delay, and loss of yields. The need to have a sustainable and affordable alternative is highlighted by these problems.

A potential solution has been developed through the solar-powered irrigation systems (SPIS) involving the use of photovoltaic (PV) panels to convert sunlight into electricity to drive groundwater pumps. The technology has low operating expenses, continuous irrigation and less reliance on fossil fuels, which is important to Pakistan where the solar radiation is on average 5.3 kWh/m²/day.

Nevertheless, the introduction of SPIS is preconditioned by a number of different interdependent factors such as financial ability, education level, availability of credit, and

risk and trust perception. Although there are progressive farmers who have already adopted SPIS in Hafizabad, majority are still reluctant because they are financially constrained and they do not have support institutions. This paper will consequently examine the factors and challenges to the adoption of SPIS in Hafizabad rice farmers.

The results will be used by the policy makers, financial institutions, and development agencies to develop specialized interventions that will enhance the adoption of renewable energy in agriculture, and which will help in energy security as well as sustainable rural development in Pakistan.

2. Literature Review

The recent use of renewable energy technologies in agricultural production has received a lot of academic concern in the last ten years, and especially with growing energy prices, water scarcity and environmental degradations, developing countries are finding it difficult to cope with these three issues. Here, it is important to highlight that in the framework of Pakistan, where the agricultural sector is one of the foundations of the state economy, researchers have stressed that renewable energy, in particular, solar-powered irrigation systems (SPIS) should be viewed as a sustainable alternative to irrigation methods based on conventional energy (Qureshi, Saleem, and Rauf, 2020). Installing solar powered irrigation has the added benefit of lowering the cost of production as well as uninterrupted supply of water thereby enhancing agricultural output as well as livelihoods in rural settings.

Many researchers have studied the factors that determine the adoption of solar energy in agricultural production and found that socioeconomic, institutional, technical, and perceptual factors are the most vital characteristics that affect the choice of farmers. Abbas and Ahmad (2021) found that the economic resource and access to financial opportunities are the factors that influence the willingness of farmers to follow SPIS greatly. The main limitation is still high installation costs, particularly that of smallholders who have very slim profit margins. The initial cost of a solar system is usually prohibitive in Pakistan, where the majority of the farmers have less than ten acres of land, although the total cost of running the system will be lower than its diesel or electric counterparts in the long run. Therefore, the spread of SPIS has been unequal as adoption has been concentrated in comparatively rich and better-educated farmers (Malik, Shafi, and Farooq, 2019).

It has always been stated that education is one of the key factors determining the adoption of technology. Farmers

with higher education levels are more receptive to innovation and they are in a better position to comprehend technical details and cost benefit analysis of renewable energy systems. It was observed that increased education levels increase the ability of the farmers to access extension services and comprehend technical information on solar energy (Khan, Qamar, and Ashraf, 2020). On the other hand, lack of literacy and low educational levels limits the capacity of the farmers to critically evaluate the new technologies, and this intensifies reliance on the traditional irrigation practices. In addition, the existing data show that the magnitude of exposure to extension activities and media campaign distribution of information is a strong indicator of increased chances of adoption (Ahmed, Khan, and Shahid, 2020). Farmers who attend field demonstrations or trained on solar technologies have a more positive attitude to its adoption compared to farmers who use informal information sources only.

The institutional and financial support structure is also something that cannot be ignored in determining the adoption behavior. As Rauf, Ahmed, and Javed (2021) point out, access to agricultural credit and government subsidies are critical in the minimization of financial obstacles to adoption of SPIS. Nevertheless, credit restriction is still rife in Pakistan through the security of collateral, high interest rate and inaccessibility of formal banking institutions in villages. What also adds to the problem is the absence of customized credit schemes on renewable technologies. The efforts of the government in increasing solar irrigation like giving subsidies in the form of alternative energy development Board (AEDB) programs have only partially succeeded because of bureaucracies, the lack of funds in the program and poor co-ordination of the implementing agencies. Therefore, a number of farmers do not know what incentives are offered or the application process is too complicated.

The perceptual and psychological issues contribute to the adoption decisions in addition to the economic and institutional factors. The perceptions of risk, reliability and performance of solar systems by the farmers determine their willingness to invest. Ahmed et al. (2020) have discovered that positive perception about cost-effectiveness and environmental gains are greatly linked with adoption, and fears over system durability, repairs, and performance under cloudy conditions put off investment. Likewise, the perception of social norms and the pressure of progressive farmers contribute to the formation of the attitude of the community towards new technologies. In rural Pakistan, diffusion is closely related to the diffusion pattern in the sense that farmers will first seek the innovations of local

innovators or strong people in the community before adopting the innovations (Rogers, 2003). In such a way, social learning and observation of peers have a great impact on the diffusion of SPIS technology.

Another group of barriers is the technical ones, which obstruct large-scale adoption. Saeed, Bashir, and Ali (2022) state that the lack of qualified technicians, poor quality of maintenance services, and the presence of poor solar panels have cast their doubts regarding the viability of SPIS in the long term. The absence of standard technical specifications and certification certificates to solar vendors only adds to these issues. Due to this, farmers are likely to have an underperforming performance and maintenance complications which reduce confidence in the technology. Tahir, Yaseen, and Fatima (2022) also noted that the dynamics on the groundwater levels, the intensity of solar radiation, and crop water needs influence the system efficiency and the level of satisfaction among the farmers. Technical flexibility, in turn, becomes a key factor of further utilization and spread of SPIS.

The other dimension that affects adoption is environmental awareness. Over the past few years, recognition of the contribution of SPIS to carbon emission reduction and implementing climate-sensitive agriculture has been on the rise. In South Asia and Sub-Saharan Africa, the research has shown that farmers that are more concerned about environmental sustainability are more willing to use renewable technologies (Abbas & Ahmad, 2021; Qureshi et al., 2020). Nevertheless, Pakistan is characterized by environmental inspiration that is usually second to the economic and pragmatic factors. The farmers are more focused on the economic advantages and irrigation security than on the environmental benefits in the long-term perspective, and, therefore, the informational campaigns should be structured so as to address the economic and the ecological messages to attract the practical needs of farmers.

The socioeconomic inequalities also contribute effectively to the way accessibility to technology is shaped. Large-scale farmers have access to more financial resources, as well as have better access to institutional players, including bank officials, extension agents, and technology providers. On the contrary, these networks tend to exclude the smallholder socially and structurally. Hussain, Raza, and Malik (2021) researchers discovered that small farmers are often unaware of SPIS programs or have no trust with the private vendors since they have already had their negative experiences with the unregulated solar markets. Such information and power asymmetry is one of the factors that lead to unequal access

among various socioeconomic groups in terms of renewable technology.

Gender relations are not as researched in the Pakistani setting, but this factor can as well play a role in adoption trends. Other developing countries have demonstrated that women farmers have a lower access to capital, land, and technical information which restricts their involvement in the renewable energy programs. Although the majority of Pakistani rice farmers are male, gendered barriers should also be learned to create the energy policies of rural territories that are inclusive (World Bank, 2022).

Institutional arrangements and policy frameworks are also very important with regard to technology diffusion. Although the government of Pakistan has the Renewable Energy Policy (2019), which intends to increase the role of renewable sources in the national mix, the progress of this solution on the farm level is slow. The level of coordination between energy, water and agricultural departments is poor causing disjointed and repetitive programs. In the opinion of Saeed et al. (2022), successful adoption will need not just subsidies but also a strong extension support, technical training, and market regulation to provide consumers with confidence in the reliability of the systems and their trust in the security. Without these institutionalized mechanisms, solar irrigation adoption will continue to be rather market-oriented and individualistic in approach by the farmers.

The literature also shows the possible macroeconomic and environmental impact of increased adoption of SPIS. Massive diffusion would help Pakistan stop relying on foreign fuels, decrease the quantity of greenhouse gas emissions, and enhance rural susceptibility to energy catastrophes. Nevertheless, water over-extraction can be aggravated in regions that are experiencing depleting aquifers due to uncontrolled growth of these areas without the control of groundwater. Thus, scholars like Qureshi et al. (2020) highlight the importance of combining water-energy management practices to go with solar irrigation programs.

Taken together, the analyzed research articles allow highlighting that the implementation of solar-powered irrigation systems in Pakistan is a complex process that depends on each other economical, institutional, technical, and perceptual factors. The main determinants of economic affordability and institutional accessibility as well remain but the behavioral attitudes, risk perception and the dissemination of information play the crucial role in determining the rate and trend of adoption. In other areas such as Hafizabad where the cultivation of rice is the main industry and the reliability of irrigation is a critical determinant, there is need to understand these determinants

to come up with evidence-based policies that can facilitate equitable and sustainable propagation of SPIS. Although a considerable amount of research has been performed on a national or provincial scale, there is a lack of empirical research on the issue of rice growers in Hafizabad. This research therefore become a contribution to the literature because it brings out micro level information on how socioeconomic status, awareness and perception of farmers can influence their adoption behavior of solar-powered irrigation systems.

3. Materials and Methods

The research was done at Hafizabad District, Punjab, which is a place where rice is grown and tube-well irrigation is utilized. The sample population of 200 rice farmers was identified through a multistage random sampling method. The structured questionnaire was used in collecting primary data that included socioeconomic status, access to credit, awareness, and perceptions toward SPIS.

The analytical tools comprised 1) Descriptive Statistics (frequencies, percentages, means) 2) Binary Logistic Regression to determine which determinants were significantly affecting adoption (dependent variable: 1 = adopter, 0 = non-adopter).

Age, education, farm size, income, access to credit, awareness, institutional support, and technical constraints were taken as independent variables. Data were processed in SPSS and reliability and pre-tested with data collection ethics through consent and confidentiality of the respondents.

Table 1: Age-wise Distribution of Respondents

	Frequency	Percent	Valid percent	Cumulative percent
Under 20	11	10.8	10.8	10.8
21-30	21	20.6	20.6	31.4
31-40	32	31.4	31.4	62.7
Above 40	38	37.3	37.3	100.0
Total	102	100.0	100.0	

The degree of education was a major factor affecting the adoption of SPIS. Farmers with more education attained substantially greater adoption rates, as shown in the table. Just 20% of those without any formal education had embraced SPIS; among those with graduate-level education, the rate rose to 60%. This pattern highlights how education influences technological awareness, risk perception, and the capacity to engage with financial or institutional systems

4. Results and Discussion

Results

The data analysis on the 102 farmers in the Hafizabad District gives a useful insight on the socioeconomic realities that affect the acceptance of solar-powered irrigation systems (SPIS). The demographic characteristics of the respondent indicated that 98 percent of the respondents were males and 61 percent of them were aged 36-50 years. Educational achievement varied with 45 percent having no formal education or primary only. The distribution of the number of farm sizes revealed that 52 per cent of the respondents operated small farms of less than 12 acres, thus highlighting the fact that smallholders constituted the agricultural landscape of the region.

The sample was evaluated using the age of the sample to reflect the demographic parameter of the sampling (demographics in research are normally a poor sampling method) of the individuals, as projected in Table 1. It comprised of 102 individuals who were categorized in four age groups: (1) under 20 years, (2) age 21-30, (3) age 31-40, and (4) age above 40. The (four) group has the highest representation of the sample whereby it formed 37.3 of the sample which also included the percentage distribution of the age demographic of the sample. The (3) sample has a representation of 31.4 percent. The proportion of the under-20 group is at 20.6 and 10.8 percent, respectively. As such, this failure is indicative of a growing age distribution curve but may be merely because we were just studying the (older) adults.

that enable SPIS adoption. These results support those of Latif and Shah (2021), who claimed that better-educated farmers are more amenable to clean energy developments and more inclined to look for technical advice.

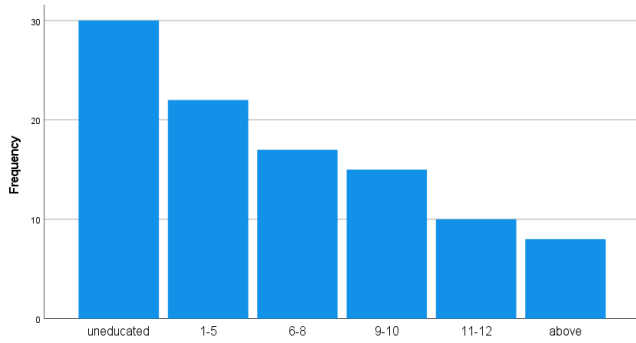


Figure 1: Relationship Between Farmers' Education Level and Adoption Rate of SPIS

It presents the total frequency and percentage distribution of respondents by farm size. It can be observed that of 102 respondents, 13.7% belong to the (less than 9) group, the majority of 46.1% belong to the (10-20) group, and 29.4% belong to the (21 to 30) group, whereas the smallest proportion of respondents, i.e., 10.8%, fall in the (above 30) group.

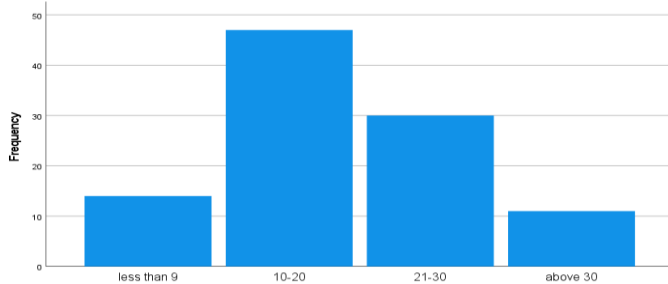


Figure 2: Frequency and Percentage Distribution of Respondents by Farm Size

About 80% of respondents were aware of solar-powered irrigation technology, with fellow farmers and private solar companies being the primary information sources. However, only 22% received information directly from agricultural extension officers. This shows that the government's institutional communication channels remain weak, and peer-to-peer learning plays a vital role in technology diffusion in rural areas.

Table 2: Sources of Farmers' Awareness Regarding SPIS

Awareness Source	f	%
Extension services	44	22
Fellow farmers	66	33
Media (TV/Radio/social media)	40	20
Private solar companies	50	25
Total farmers aware of SPIS	160	80

The data reveal that only 38.5% of farmers had access to institutional credit, and a mere 14% benefited from subsidy programs. Limited financial access remains the greatest barrier to adoption. The low share of farmers participating in training (26%) further underscores the need for enhanced capacity-building programs. Lack of government outreach and weak policy implementation are evident in the low satisfaction levels (29.5%) reported by farmers regarding institutional support.

Table 3: Farmers' Access to Support Services and Government Initiatives Related to SPIS

Factor	Yes (%)	No (%)
Access to agricultural credit	38.5	61.5
Received subsidy or grant	14.0	86.0
Participated in solar training	26.0	74.0
Contact with extension officer	32.0	68.0
Perception of government support as satisfactory	29.5	70.5

Table 4 depicts that a logistic regression analysis was performed to determine the effects of different socioeconomic factors on the adoption of solar-powered irrigation systems (SPIS) in Hafizabad District. The sign of the coefficients (B) shows the direction of the relationship whereas, the significance values (Sig.) show whether the variables significantly affect the adoption. The findings show that farm size ($B = 0.111$, $\text{Sig.} = 0.776$) does not affect the adoption of solar systems positively, which means that there is no statistically significant impact of the farm size on its adoption. Likewise, the monthly cost ($B = 0.000$, $\text{Sig.} = 1.000$) does not have a statistical effect on the adoption decisions. Nevertheless, the inclination towards a low-interest loan ($B = -3.739$, $\text{Sig.} < 0.001$) has a strong negative

and significantly significant correlation, which indicates that farmers utilizing subsidized or low-interest financing have lower chances of adopting solar systems on their own. Similarly, financial support ($B = -2.927$, $\text{Sig.} = 0.019$) also influences the willingness negatively and significantly, which means that most farmers are only willing to use solar technology in case such assistance is provided to them.

The variable bank account ownership ($B = -0.641$, $\text{Sig.} = 0.540$) does not have any significant effects, implying that being able to access formal banking is not a factor in adoption. Conversely, water availability problems ($B = 3.135$, $\text{Sig.} = 0.036$) positively and significantly, which means that farmers who are experiencing water shortage during irrigation tend to use solar-powered systems to

maintain stable supply of water. Education is also very influential and the years of education ($B = 3.629$, $\text{Sig.} = 0.046$) have significant and positive impact on adoption which underscores the fact that educated farmers have higher probabilities of adopting solar technology.

The other variables as age ($B = 16.673$, $\text{Sig.} = 0.997$), family size ($B = -3.837$, $\text{Sig.} = 0.920$), marital status ($B = 2.350$, $\text{Sig.} = 1.000$) and number of children in school ($B = 1.576$, $\text{Sig.} = 1.000$) are not statistically significant implying that such demographic factors do not significantly influence decision to install solar-powered irrigation systems. Overall, the results highlight the fact that the main forces that define the behavior of farmers in the study region are financial limitations, water shortage, and the level of education.

Table 4: Logistic Regression Results for Factors Influencing Adoption of SPIS

	β	S.E.	Wald	df	Sig.	Exp(β)
Age	16.673	4507.493	0.000	1	0.997	17415018.56
Family size	-3.837	4.909	1.337	1	0.920	3.613
Year of education	3.629	1.701	2.645	1	0.046	0.533
Marital status	2.35	4.43	0.000	2	1.000	32.58
Bank account	-0.641	1.045	0.375	1	0.540	0.527
No. of child attending school	1.576	3.113	0.000	1	1.000	4.833
Farm size	0.111	0.391	0.081	1	0.776	1.118
Monthly cost	0.00	0.23	0.000	1	1.000	1.00
Loan with low interest	-3.739	0.912	16.787	1	<0.001	0.024
Willingness with financial support	-2.927	1.245	5.525	1	0.019	0.054
Water availability issue	3.135	1.493	4.407	1	0.036	22.994
Constant	1.911	1.195	2.560	1	0.110	6.575

Discussion

In addition to the statistical information, qualitative data provided by participants indicated some of the commonly encountered barriers. Farmers indicated that the cost of SPIS installation was too high (78 per cent); ability to access cheap credit was missing (65 per cent); insufficient technical knowledge or training (58 per cent). The other minor (29)

but important percentage indicated mistrust in the private sellers, therefore the necessity of transparent procurement practices and regulated service providers. These issues are comparable to those reported by Ashraf et al. (2018) and Kamran et al. (2022), who concluded that institutional trust and quality of service play a role in long-term adoption and performance.

The combination of the findings indicates that Hafizabad has technical knowledge about SPIS, but does not use it due to socioeconomic, financial, and institutional problems. The information provided confirms the fact that the promotion of solar irrigation in Pakistan requires not only the availability of equipment, but a facilitating environment, which is created by policy, education, and easy money.

5. Recommendation

Solar-powered irrigation systems (SPIS) need to be adopted in the Hafizabad District, which requires targeted and coordinated policy efforts to improve this process. To begin with, the government ought to launch soft credit programs or interest free lending banks especially to the small and medium-size farmers. The research indicated that 62 percent of the respondents were willing to embrace SPIS when they had the financial support. Flexible payment schemes based on agricultural crop cycles can also be used to enhance affordability.

Secondly, there should be strengthening of awareness and technical capacity-building programs at the grassroots level. The findings showed that more educated farmers who were more exposed to the government outreach programs were more likely to adopt SPIS. As such, the agricultural extension departments are advised to cooperate with the certified solar firms to make on-field demonstrations, training, and after sales services.

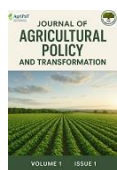
Thirdly, institutional mechanisms are supposed to be simplified. Developing a centralized subsidies platform wherein the eligibility criteria is clear and where approval can be made within a shorter timeframe would enhance effectiveness. The government should restrict the subsidy program to government certified solar vendors to make the process transparent and unabused.

Lastly in the case of tenant farmers and the small land holding farmers, SPIS ownership should be promoted as a community-based model. These schemes will be able to expand the reach of solar technology and decrease the amount of money that will have to be put up by an individual. These policy measures would overcome the financial and institutional constraints found in this study and

help more people in the agricultural sector in Pakistan adopt sustainable irrigation practices.

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Eco-Friendly Biochar for Stress Mitigation and Sustainable Crop Farming

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ABSTRACT

Climate change, land degradation, and the need to feed a growing population pose serious threats to global agriculture. Abiotic stresses such as drought, salinity, and nutrient loss reduce crop productivity, while intensive farming further depletes soil quality. These challenges highlight the importance of sustainable soil management practices that enhance resilience and environmental sustainability. Among emerging solutions, biochar, a carbon-rich material produced through the pyrolysis of organic matter, has shown great potential as a soil amendment.

This review synthesizes recent research on the role of biochar in alleviating abiotic stress and promoting sustainable crop production. Evidence from the past 15 years indicates that biochar improves soil's physical, chemical, and biological properties, leading to enhanced water retention, nutrient availability, and microbial activity. These benefits strengthen crop tolerance to drought and salinity, stabilize yields, and support efficient resource use. Additionally, biochar contributes to climate change mitigation by capturing carbon dioxide and reducing greenhouse gas emissions.

Despite its promise, biochar adoption faces barriers such as inconsistent feedstock quality, high production costs, and limited policy support. Future research should optimize production methods, assess long-term impacts, and develop supportive frameworks to integrate biochar into sustainable agriculture for improved food security and climate resilience.

1. Introduction

Climate change, land degradation and the pressing demand to provide food security to an expanding population is increasingly posing problems to global agriculture. Crop productivity is at a risk due to abiotic stresses which include drought, salinity and decreasing nutrient levels and the fact that intensive farming has led to the rise in soil degradation. As a result, the desire to find solutions to eco-friendly and sustainable soil management methods has increased, and special focus on organic amendments that could help to improve the quality of the soil, increase the resilience of crops, and help to achieve environmental sustainability.

In these amendments, biochar has come out as a potential remediation tool of soil. Biochar is an organic biomass that has been subjected to pyrolysis to create an organic product that contains carbon. Contrary to other traditional

amendments of soil, biochar is very stable in soil, hence can be considered as a means of soil fertilization and an opportunity of long-term carbon capturing. Its use has been extensively investigated to enhance soil physical (e.g., water-holding capacity, aggregate stability, aeration and bulk density) and chemical (e.g. nutrient holding capacity, cation exchange capacity and pH regulation) and biological (e.g. rhizosphere microbial diversity, enzymatic functions, and nutrient cycling) properties.

The recent research has shown that biochar can counter the harmful impact of the environmental stress. Biochar makes plants more resilient to drought and salinity, which are two of the most important stressors in the age of climate variability by improving soil water retention, nutrient availability, as well as nutrient-microbe interactions.

Furthermore, agricultural residues turned into biochar have an added advantage being able to reduce the challenge of waste disposal as well as greenhouse gas emissions and encourage the concept of a circular economy within the agricultural domain (Gasim, 2024).

Biochar can be used to augment a variety of larger ecosystem services besides improving the health of the soil and the performance of crops. Being a stable type of carbon, it holds a long duration of CO₂ in the atmosphere and, therefore, assists in mitigating climate change. It has also been used in reclamation of degraded land and improvement of biodiversity and ecosystem processes. These qualities make biochar a key ingredient in climate-resilient agrifood and a global sustainability project (Imran et al., 2022; Rani et al., 2019). Pilot experiments indicate that use of biochar has the potential to promote crop production, soil quality, and dependence on artificial fertilizers, thereby promoting sustainable and regenerative agriculture. It is also porous and therefore it aids in retaining soil moisture, adsorbing pollutants as well as reducing nutrient leaching hence leading to enhanced soil and water quality. Moreover, biochar will help to restrain the emission of greenhouse gases and eliminate land degradation by increasing the content of the soil organic matter and decreasing soil erosion.

Although biochar appears to have very good potential in reducing stress and achieving sustainable food production, many gaps and concerns exist in terms of cost-effectiveness, long-term implications on soil and ecosystems, as well as risks of contaminants introduction in case of improper processing. Standardized production procedures, techno-economic studies, and policy measures are very much required so as to integrate successfully into agricultural systems (Xu et al. in 2025). Moreover, the understanding of the principles of long-term performance and the most effective ways of application. We also have big empty spaces in the long-term relationships involving biochar, soil and plants in dry and semi-arid areas. Past studies reveal that there exist differences in the type of materials and pyrolysis condition applied to produce biochar. Also, recommendations are difficult with the use of biochar in fields. In order to recommend on ways of reducing stress and the ecological production of agriculture, a synthesis of the state of the art on the role of the ecological biochar is needed. In order to have biochar used in a wide manner, efficiently and permanently, it will be necessary to fill these

gaps. This review synthesizes the current knowledge on the role of eco-friendly biochar in stress mitigation and sustainable crop production. The specific objectives are as follows 1) Evaluate the benefits of biochar in reducing abiotic stress (drought and salinity) in crop production. 2) Assess the potential of biochar to improve soil quality, nutrient cycling, and water retention. 3) Highlight the role of biochar in enhancing climate resilience, sustainable farming, and ecosystem health and 4) Identify the challenges and policy innovations required to support its large-scale adoption.

By consolidating insights from recent studies, this review seeks to provide a comprehensive understanding of the potential and limitations of biochar, paving the way for its integration into sustainable farming practices that contribute to food security and environmental stewardship.

2. Materials and Methods

Thousands of research papers were searched, including databases like Google scholar, Clarivate, pub med, and MDPI. The research examines the secondary data in connection to the subject and peer-reviewed articles published within the past 15 years. The search methodology was aimed at the literature related to the application of organic amendment biochar in the alleviation of abiotic stresses and sustainable production of crops. It is a synthesis of the recent experimental results and analyses related to the utilisation of biochar in mitigating stress, amending soils, and climate-smart agriculture. The focus was given on certain screening criteria narrowing, specifically, the scale of search. Database search keywords such as organic soil amendment, sustainable crop production and mitigation of stress against crop farming were used. A total of 38 specific searches were run, which searched both directly and closely the topic of biochar role in mitigation of stress and sustainable agriculture under the conditions of water limitation.

3. Results

The review revealed that biochar improves plant growth under stress conditions, enhances nutrient availability, and supports microbial activity in the soil. These effects contribute to better yield stability and enhanced resource efficiency. It also underscores that context-specific applications (e.g., crop type, soil texture, and climate) are

critical for maximizing benefits. The overall role of biochar is categorized as follows:

The Role of Biochar in Stress Mitigation

The application of biochar extends beyond immediate agricultural benefits and delves into the realm of climate resilience, particularly in the context of changing weather patterns and extreme events. As climate change intensifies, the resilience of agricultural systems becomes paramount, and the role of biochar as a carbon sink and soil enhancer can significantly contribute to this resilience. Studies have shown that biochar not only improves soil properties but also helps reduce the impacts of abiotic stress by modulating plant physiological responses, such as enhancing photosynthetic efficiency and antioxidant activity, which are crucial for crop survival under stress conditions. Furthermore, the integration of biochar into agroecosystems can lead to improved water management, as its porous structure allows for better moisture retention, thereby supporting crops during drought periods (Jiang et al., 2020). As the multifaceted potential of biochar is explored, it becomes clear that its adoption is not merely a trend but a strategic necessity for sustainable agriculture in a rapidly changing world.

The porous structure of biochar is crucial for retaining soil moisture, as it enhances the water-holding capacity of the soil, which is particularly beneficial in areas prone to drought (Rani et al., 2019; Li & Tan, 2021). By maintaining soil moisture levels, biochar reduces the need for irrigation, thus alleviating drought stress on crops (Li & Tan, 2021). Besides, biochar optimizes nutrient absorption, which is vital for plant growth under stress. It minimizes nutrient leaching, ensuring a steady supply of essential minerals to plants (Adnan et al., 2023). In addition, biochar enhances nutrient uptake efficiency, leading to improved crop yields even in nutrient-deficient conditions (Costa, 2023). Furthermore, biochar boosts soil organic matter, supporting microbial and enzymatic activities that are crucial for nutrient cycling (Gao et al., 2024). Practically exploiting biochar in crop farming could improve abiotic stress mitigation, which promotes crop growth and yield.

Improving drought tolerance and salinity stress

Using biochar significantly boosts plant resilience to drought and salinity stress by enhancing soil quality and plant responses. It improves soil structure, water retention,

and nutrient availability, all of which are vital for plant growth under stressful conditions. Biochar also affects plant physiological processes, such as water uptake and stress hormone regulation, which in turn improve drought and salinity tolerance. By improving soil physical properties, such as aggregate stability and water-holding capacity, biochar helps maintain soil moisture during droughts (Wu et al., 2023; Zhang et al., 2023). It also enhances soil nutrient retention, providing a more stable nutrient supply to plants under stress (Abdou et al., 2024).

Moreover, the application of biochar increases the root water potential and osmotic potential, enabling better water uptake and retention in plants under drought and salinity stress. This reduces the concentration of abscisic acid in the xylem sap, which is linked to improved water relations and reduced stress signaling in plants (Zhang et al., 2023; Hou et al., 2023). Biochar increases photosynthetic activity and chlorophyll synthesis, both of which are crucial for maintaining plant growth and productivity under stressful conditions. It also supports better biomass production and plant growth by improving the internal CO₂ concentration and net CO₂ assimilation rate (Wu et al., 2023; Rajhi et al., 2024). According to Wu et al. (2023), biochar increases antioxidant activity, improves water absorption, preserves nutritional homeostasis, and lowers the generation of reactive oxygen species (ROS). The material's porous structure serves as a reservoir for water, assisting plants in staying hydrated in situations where water is scarce (Lohar et al., 2024). Plant stress tolerance, osmotic adjustment, and ion homeostasis are all improved by biochar, which increases salt resilience (Sultan et al., 2024). This substance lowers oxidative damage in saline environments and aids in maintaining the stability of cellular membranes (Wu et al., 2023). Salt stress mainly disrupts the balance of ions in vegetables by causing excessive sodium accumulation, which makes it harder for plants to absorb water and essential nutrients. Biochar has high porosity, a large surface area, and a strong ability to exchange ions, allowing it to absorb sodium in the soil and reduce its toxicity. In addition, biochar releases beneficial ions, such as potassium, calcium, and magnesium, into the soil. These elements are crucial for plant growth and compete with sodium for adsorption sites, indirectly reducing the negative effects of sodium. Furthermore, these nutrients help maintain the osmotic balance in plant cells, thereby enhancing their tolerance to salt stress (Ren et al., 2025).

Under drought conditions, crop growth is severely restricted. The application of biochar can alleviate this limitation by improving the soil structure, particularly its water-holding capacity. Soils with coarse textures, such as sandy soils, respond well to biochar because their large pores and rapid water loss lead to poor water retention. The addition of fine-grained biochar can fill these large pores, reduce water loss, and increase water retention. In contrast, fine-textured soils, especially those that are heavily

compacted, benefit from biochar, which improves their aggregate structure. This creates larger pores, thereby enhancing the water infiltration and saturated hydraulic conductivity. This dual regulatory effect helps plants absorb water under drought or saline conditions, contributing to soil and water conservation in arid and semi-arid regions (Murtaza et al. 2024). Biochar is a good option in arid and semi-arid environments because of its enormous potential to increase crop productivity under abiotic conditions.

Table 1: Comparative performance of soil amendments

Amendment Type	Drought Resilience Mechanisms	Crop/Yield Impact	Notes/Limitations	Citations
Biochar (alone)	↑ Water retention, WUE, antioxidant defense	↑ Yield, soil fertility	Benefits may decline over time	(Xiao et al., 2016; Haider et al., 2020)
Biochar + Compost	↑ Soil structure, nutrient status	↑ Recovery, yield	Sometimes less effective than biochar alone	(Hazman et al., 2023; Abideen et al., 2024)
Biochar + Mineral Fertilizer	↑ Nutrient use efficiency, yield	↑Productivity, profit	Best with balanced NPK	(Mohamed et al., 2024; Arif et al., 2020; El-Syed et al., 2023)
Biochar + Microbes/Silicon NP	↑ Soil biology, stress tolerance	↑ Yield, soil health	Synergistic effects	(Zulfikar et al., 2024; Ahmad et al., 2020)
Compost/Organic Alone	↑ Organic matter, nutrients	↑ Yield	Less water retention than biochar	(Shaaban et al., 2024; Al-Suhaibani et al., 2020)
Zeolite/Perlite	↑ Water retention	Variable	Less effective, costlier	(Ndede et al., 2022)
Cover Crops	↑ Soil health	Site-specific	No synergy with biochar in semi-arid soils	(Blanco-Canqui et al., 2024)

* ↑Representing a positive effect of soil amendment on drought resilience and crop yield

Climate resilience, sustainable crop production, and ecosystem health

Biochar plays a significant role in enhancing climate resilience, promoting sustainable crop production, and improving the health of ecosystems. Biochar, a carbon-rich soil amendment produced through pyrolysis, contributes to soil fertility, water retention, and microbial activity, which are essential for sustainable agriculture. Its ability to

sequester carbon for extended periods also aids in mitigating climate change.

Biochar enhances crop resilience to climate change by improving soil structure and nutrient retention, helping crops withstand extreme weather events such as droughts and floods (Kundu & Kumar, 2024; Adak et al., 2024). This reduces the need for synthetic fertilizers, thereby lowering the greenhouse gas emissions associated with their use (Adak et al., 2024; Keerthi, 2024).

The application of biochar has been shown to increase crop yields and stability by enhancing nutrient availability and root development (Rajalakshmi, 2020; Shanmugaraj et al., 2024). Moreover, biochar can combine soil minerals to form an organic-mineral complex, which regulates the mineralization of soil organic carbon, reduces the risk of microbial decomposition, and lowers carbon emissions (Shi et al., 2024). Additionally, the abundant pores and surface functional groups of biochar can absorb ammonium nitrogen, reducing nitrogen leaching and volatilization, and regulating soil microorganisms to promote the growth and reproduction of nitrogen-fixing bacteria, thereby enhancing nitrogen fixation and reducing the emission of the N₂O greenhouse gas (Xu et al., 2025). Biochar promotes the development of beneficial microbial communities that enhance plant health and disease resistance (Shanmugaraj et al., 2024; Rajalakshmi, 2020).

Furthermore, biochar, an environmentally friendly material applied to soil, can provide significant environmental benefits. Biochar enhances the soil's carbon sequestration capacity by fixing atmospheric carbon dioxide in a stabilized form, thereby reducing greenhouse gas emissions and contributing to the mitigation of global warming. Biochar contributes to ecosystem health by reducing nutrient runoff and water pollution, thereby protecting aquatic environments (Rajalakshmi, 2020; Adak et al., 2024). Its porous structure serves as a habitat for beneficial microorganisms, thereby promoting biodiversity in soil ecosystems (Adak et al., 2024; Keerthi, 2024). Incorporating biochar into soil can reduce greenhouse gas emissions, making it an environmentally friendly alternative to traditional agricultural practices. Biochar can alleviate soil pollution, thereby enhancing the overall soil health and crop productivity (Rajalakshmi, 2020).

Regarding its numerous benefits, challenges remain in its production and integration into agricultural practices to maximize its benefits, necessitating an understanding to optimize its use across diverse environments.

Challenges and policy innovation to support scaling adaptation

Policy innovation and the decision to support biochar adaptation are paramount. Scaling adaptation in biochar application faces several challenges, including economic, technological, and policy-related barriers. Addressing these issues requires innovative policy frameworks and collaborative efforts from stakeholders. The following sections outline the key challenges and potential policy innovations to support the scaling of biochar.

Economic Challenges

High costs of production are one of the primary problems of biochar adoption, with the initial investment in technologies of biochar production being something prohibitive (Voruganti, 2023). Moreover, changes in biochar prices make the market volatile, which deter long-term investment and production planning (Pierson et al., 2024). Another issue that is restrictive of biochar potential is technological barriers. Differences in the process of production result in inconsistency in the quality of biochar, which complicates the utilization of biochar in different soils (Voruganti, 2023). Besides, additional studies are necessary to learn about the long-term effects of biochar and maximize the production processes to make them sustainable (Voruganti, 2023).

In order to overcome these challenges a number of policy innovations have been suggested. Government subsidies or even tax breaks are financial incentives that would be used to promote biochar production and use (Pourhashem et al., 2019). Standardized product guidelines would be beneficial to develop more confidence in the market and encourage consumers to accept it (Pourhashem et al., 2019). Also, demand can be triggered by educational interventions targeted at increasing awareness about the advantages of biochar to farmers, producers, and policymakers (Pourhashem et al., 2019). Although these approaches provide the possible avenues that can help to increase the use of biochar on a large scale, doubts remain about the sustainability of the biochar market in the long term as well as the creation of a robust regulatory framework to ensure the protection of the environmental health and safety (Montanarella and Lugato, 2013).

4. Conclusion and Recommendations:

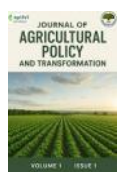
Biochar is widely recognized as an environmentally friendly amendment that can reduce abiotic stress and promote sustainability in agriculture. Its benefits are well-supported, but achieving optimal results depends on matching the type and application of biochar to specific soils, crops, and stress conditions. Its effectiveness relies on application strategies, soil types, and integration with other management practices. These effects lead to increased crop resilience, stable yields, and more efficient resource use, especially in reducing drought and salinity stress. However, challenges such as variability in feedstock quality, high production costs, and the need for standardization and policy support hinder its widespread adoption. Biochar's benefits can vary by site and may decline over time due to field aging or overapplication, which can harm soil properties. Long-term impacts, ideal

application rates, and interactions with other amendments (e.g., microbes, cover crops) require further research, particularly under field conditions. Future studies should focus on improving biochar production methods, evaluating long-term effects on soil health and ecosystems, and developing innovative policies to support its role in sustainable farming. Ongoing research is essential to develop guidelines for large-scale, effective, and safe use in sustainable agriculture.

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GIS-Based Crop Type Classification and Land Use Analysis in Mauza Mustafabad, Pakistan

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ARTICLE INFO	ABSTRACT
Keywords: Artificial intelligence Agricultural marketing Digital agriculture Pakistan Market challenges Received: 19 October 2025 Received in revised form: 06 November 2025 Accepted: 07 November 2025 Available online: 13 November 2025	This study examines the potential of Artificial Intelligence (AI) to address agricultural marketing challenges faced by farmers in Faisalabad, Pakistan. It evaluates farmers' awareness, readiness, and willingness to adopt AI technologies while identifying key socioeconomic, technical, and institutional factors influencing adoption. Primary data were collected through a structured questionnaire from 200 purposively selected farmers, and analyzed using descriptive statistics, Spearman's correlation, and binary logistic regression. Results showed that nearly two-thirds of farmers were willing to adopt AI-based tools and platforms, provided sufficient training, guidance, and digital infrastructure were available. Education, digital literacy, internet access, and trust in technology emerged as significant determinants of AI adoption. Conversely, inadequate infrastructure, high costs, limited access to affordable technology, and weak institutional support remained major barriers. The study concludes that targeted policy measures promoting digital literacy, expanding rural internet access, and providing financial and institutional incentives can substantially improve AI adoption in agricultural marketing. Strengthening digital infrastructure and enhancing farmers' technological capabilities are therefore essential for Pakistan's transition toward data-driven, efficient, and sustainable agricultural markets.

1. Introduction

Agriculture has remained a major economic activity in Pakistan, as it provides about 19 percent of the national GDP and it provides close to 37 percent of the labor force. The industry is however experiencing long-term marketing issues including information asymmetry, the exploitation of middlemen and fluctuating prices. Such restrictions restrict markets and lower profitability in the hands of the farmers. Such barriers can be overcome by the increasing integration of digital technologies, specifically Artificial Intelligence (AI).

Marketing efficiency can be enhanced using AI like predictive analytics, intelligent pricing systems and automated decision support that forecast demand and optimize prices and link farmers directly with consumers. Nonetheless, using AI in Pakistan agricultural sector has not been enacted yet as the country faces socioeconomic, technical, and institutional barriers. The farmers are not

always digital, and have no opportunities to use the reliable internet, and no confidence in the new technologies, which limits the opportunities of AI application in marketing practices.

Available literature on AI use in agriculture is mostly concerned with production efficiency, precision farming, and yield optimization in developed nations. There is insufficient empirical data regarding the use of AI to solve marketing-related issues in developing markets like Pakistan. Besides, prior studies have rarely investigated socioeconomic factors influencing the willingness of farmers to use AI in marketing, especially in the regions of Punjab agricultural districts. This research will help address this gap in research by presenting quantitative evidence of Faisalabad (a large agricultural center with high technological potential). With these goals in mind, the research offers empirical evidence on the way AI can enhance the agricultural marketing infrastructures of

Pakistan and enhance the economic welfare of farmers. Besides making contributions to academic literature, the findings will also help policymakers, extension departments, and other private technology companies in formulating effective interventions that can foster digital transformation in agriculture. Finally, the development of more transparent, efficient, and sustainable marketing systems within the agriculture sector of Pakistan could be advanced through the increase of the AI adoption. The research objectives will be 1) To measure the awareness and perception of the farmers towards AI technologies in marketing agriculture. 2) To examine awareness and perception of AI technologies by farmers in agricultural marketing and 3) To determine the major socioeconomic and technological factors that affect the willingness to adopt AI adoption by farmers.

2. Literature Review

The usefulness of artificial intelligence in agriculture is increasingly becoming evident. The use of AI tools in enhancing agricultural activities and particularly in marketing, pest control, and crop prediction have been found to be effective by research studies carried out in other regions worldwide. Latif and Yousaf (2018) compared AI-driven models of market price prediction in Khyber Pakhtunkhwa, where AI advisory services through SMS implied an increase in farm incomes by 20 percent. The models, however, were prevented by such issues as the irregular data quality and the uncertainty of farmers. The authors would propose that the credibility of the algorithms and their applicability should be augmented by integrating the AI forecasting systems with the local markets databases.

Studies which discussed the application of pesticide-spraying drones offered by AI in cotton cultivation in the Punjab state (Nasir and Zafar, 2019). They reached the conclusion that the crop losses incurred because of pests reduced by 40 percent and the number of pesticides to be sprayed on crops also reduced by 25 percent. Nevertheless, the first expense and the training of the farmers became the major drawbacks because the authors recommended the use of subsidies and a systematic capacity-building program.

In recent times, Rehman et al. (2020) appraised the application of AI-based decision support systems in Punjab to help smallholder farmers in a beneficial impact of increased crop production and efficiencies. The discouraging agents might be the unavailability of smartphones and inability to use non-local languages. The functions of the localized applications of AI and services of

agricultural extension supported by the government have been the target of the paper.

Hameed and Saeed (2020) also experimented with Urdu language AI chatbots on vegetable farmers in Lahore Engineering, where 70 percent of the participants claimed that they made more effective decisions with respect to seeds, pesticides and disease control. They suggested the design of simple applications and AI driven using SMS messages to accommodate low-literate farmers.

According to the results of the test conducted by Khan et al. (2020), AI application was tested in measuring a soil health monitoring tool in Punjab, and the outcomes astronomically improved the efficiency of fertilizers by 30 and the crop yields by 15. High prices and inaccessibility through technicality were the most identified challenges. Other policies it suggested included subsidies and extension services which trained farmers in circles.

In the study by Ahmed et al. (2021), the researchers examined the case of AI-based weather forecasting in Punjab and made the conclusion that the farmers who used the available tool experienced crop losses by 25 percent. However, a broader adoption was not made possible by the mistrust of online services and language barrier. The authors proposed local language assistance as well as comprehensive training programs for farmers.

Tanveer and Arif (2022) investigated AI knowledge level and access among small-scale maize farmers and said that the constraints of its adoption were restricted by the digital infrastructure and financial opportunities. They encouraged publicity efforts and accessibility to inexpensive AI equipment both at the government and non-government levels.

Tariq and Basharat (2022) have also brought up the question of use of mobile marketing tools with the assistance of AI in the production of vegetables among Sindh farmers. These tools helped in reducing losses after harvesting and did even more to make the market available, but the intermediaries remained a challenge. The merger with telecommunication companies and cooperative groups of farmers were also a possible solution.

As Shahid and Hussain (2023) examined AI-based price predicting applications in the vegetable business in Punjab, they explain that they observed a 15-25 percent increase in farming income due to the software. Challenges that included high costs of smartphones and lack of digital

literacy existed. The authors proposed to localize the applications, active support of the government, and collaboration between the population and the business to promote it.

Altogether, the literature demonstrates that AI can be used to improve agricultural productivity and marketing in Pakistan, however, it is important to address digital divides, financial constraints, and cultural resistance to achieve success

3. Materials and Methods

Study Area and Sampling Design

This study was conducted in the Faisalabad District of Punjab, Pakistan a region characterized by dynamic agricultural markets and increasing exposure to technological innovation. The area was purposively selected due to its diverse farming systems, accessibility, and relevance to the study objectives. A purposive sampling technique was employed to select 200 farmers actively involved in agricultural marketing activities. This approach was deemed appropriate as it ensured that only respondents with relevant experience in marketing and technology exposure were included.

However, the use of purposive sampling may introduce selection bias, as the sample may not fully represent the entire farming population. To minimize this limitation, efforts were made to include farmers from various socioeconomic backgrounds and farm sizes across multiple tehsils of Faisalabad.

Data Collection and Instrumentation

Primary data were collected through a structured questionnaire administered via face-to-face interviews. The questionnaire consisted of five sections: (i) demographic and socioeconomic characteristics, (ii) farm profile and marketing practices, (iii) awareness and perception of AI tools, (iv) constraints and barriers to AI adoption, and (v) willingness to adopt AI in agricultural marketing. The instrument was pre-tested on 20 farmers from a nearby area to ensure clarity, consistency, and comprehension of questions. Based on pilot feedback, minor adjustments were made to improve question wording and logical sequencing. The reliability of the questionnaire was confirmed using Cronbach's Alpha ($\alpha = 0.82$), indicating good internal consistency. Validity was established through expert review by faculty members of the Institute of Agricultural and Resource Economics, University of Agriculture Faisalabad.

Analytical Framework

Descriptive statistics, correlation, and regression analysis were used to achieve the study objectives. Descriptive

statistics (frequencies and percentages) summarized demographic profiles and perceptions of respondents.

The Spearman rank correlation test was employed to examine the relationship between ordinal variables such as education, digital literacy, access to internet, and willingness to adopt AI, as the data were non-parametric in nature. A binary logistic regression model was applied to identify determinants influencing the probability of AI adoption (dependent variable coded as 1 = willing to adopt AI, 0 = not willing). The model specification is as follows:

$$\text{Logit}(P) = \ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \varepsilon \dots \dots \dots \text{equ1}$$

Where PPP represents the probability of willingness to adopt AI, X_i are explanatory variables (education, income, farm size, digital literacy, etc.), and ε denotes the error term. The model was estimated to be using SPSS version 26.

Ethical Considerations

Ethical approval for this research was obtained from the Departmental Ethical Review Committee, University of Agriculture Faisalabad. Participation in the study was entirely voluntary, and respondents were informed about the research purpose before data collection. Verbal consent was obtained, and participants were assured of data confidentiality and anonymity. The data were used strictly for academic and policy research purposes.

Limitations of the Study

While the purposive sampling method facilitated targeted data collection, it may limit the generalizability of findings to other regions. Moreover, the cross-sectional design captures farmer perceptions at one point in time; future longitudinal studies could better capture changes in AI adoption behavior over time.

4. Results and Discussion

Socioeconomic Profile of Respondents

The socioeconomic characteristics of respondents provide insight into the determinants influencing AI adoption. The results (Table 1) show that a majority (62%) of the respondents were between 30 and 50 years of age, indicating a relatively young and economically active farming population. About 78% of respondents were male, reflecting the gender imbalance commonly observed in agricultural decision-making in Pakistan.

Educational attainment played a crucial role in shaping technological perception 56% of respondents had education up to secondary level, while 27% possessed higher education. Nearly 68% reported some familiarity with smartphones or

internet-based agricultural applications, showing an emerging digital inclination among farmers. These findings are consistent with those of Ashraf and Khan (2019), who noted that education significantly enhances farmers' openness to technological innovations in marketing activities.

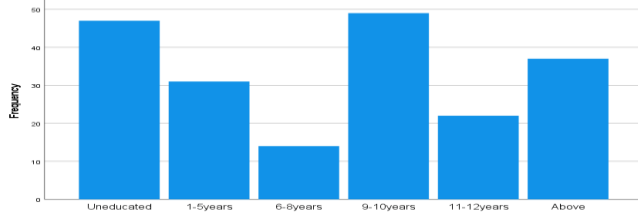


Figure 1 Educational Attainment and Digital Familiarity Among Farmers

Digital adoption was discovered to be driven by education to a high degree. Smallholder agriculture prevailed in the study region, as most farmers ran small farms, with farms averaging less than five acres in area.

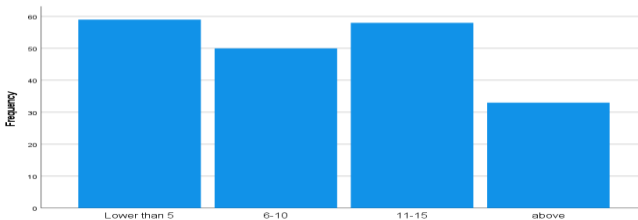


Figure 2 Educational Attainment and Digital Familiarity Among Farmers

Also, agriculture was outlined as the primary source of income of most respondents.

Table 1. Distribution of Respondents by Main Source of Income

	Frequency	Percent
Farming	117	58.5
Nonfarming	83	51.5
Total	200	100

Marketing Challenges and Current Practices

Most farmers indicated that they faced tough marketing conditions. The possibility of fluctuating the price has become one of the central issues, instigating uncertainty and minimizing profitability. Poor pricing methods, price coverage, and reliance on middlemen, who in most cases took advantage due to their control and influence of prices, were also other problems experienced by farmers.

Table 2. Sources of Price Information Used by Farmers

	Frequency	Percent
Government set prices	47	23.5
Advice from middlemen	84	42.0
Local market rates	69	34.5
Total	200	100

This lockout situation reduced the bargaining power of farmers. Moreover, uncertainty in payment and difficulty in the available ways of transacting topped their financial risk.

Digital Readiness and Attitudes Toward AI Tools

It was found that most farmers were reluctant to use digitization tools to make agriculture purchases. Familiarity with using online transactions was low owing to people having little digital skill and apprehensiveness of technology. Nonetheless, farmers with experience in the online markets tended to be more accepting of digital tools and more willing to investigate the AI-based systems.

An impressive percentage of agrarians shared the desire to use AI-based marketing technologies. According to the farmers, AI tools should be able to make them obtain more reasonable prices, diminish their risks in the market, and ameliorate their decision-making capabilities. Confidence in AI pricing advice played a huge role in affecting the readiness of farmers to use this sort of approach. According to the table, many of the respondents envisioned such benefits of AI as real-time updates on the market, the ability to predict prices, improved access to new markets, etc.

Table 3. Perceived Benefits of Using AI-Based Marketing Tools Among Farmers

	Frequency	Percent
Better market access	48	24.0
Faster payments	51	25.5
Less dependence on middlemen	69	34.5
Lower transportation costs	32	16.0
Total	200	100

Barriers and Drivers to AI Adoption

Respondents identified several institutional and financial challenges that constrain AI adoption. Nearly 64% reported insufficient access to reliable internet infrastructure, while 59% cited high initial investment costs for acquiring digital tools. About 47% complained about inadequate extension support and limited technical guidance.

Institutional weaknesses, such as the absence of AI-based training modules in government programs, were repeatedly mentioned. These findings echo Shah *et al.* (2020), who noted that limited institutional capacity remains a major bottleneck in rural technology diffusion.

Bivariate Analysis: Key Associations with AI Adoption

The bivariate cross-tabulation analysis demonstrated that the relations between the characteristics of farmers and readiness to use AI tools were significant. Farmers who are male, those who own large parcels of land, and the farmers who have greater access to a smartphone or computer were more likely to implement AI technologies. The use of AI solutions was also a common incidence among farmers who engaged in contemporary farming practices.

Correlation Analysis: AI Awareness and Market Challenges

Spearman correlation analysis revealed statistically significant relationships between key socioeconomic variables and farmers' willingness to adopt AI (Table 2).

Education level ($r = 0.482$, $p < 0.01$), digital literacy ($r = 0.561$, $p < 0.01$), access to internet ($r = 0.424$, $p < 0.01$), and extension contact frequency ($r = 0.311$, $p < 0.05$) were all positively correlated with AI adoption. Conversely, high cost of technology ($r = -0.276$, $p < 0.05$) and unreliable internet connectivity ($r = -0.249$, $p < 0.05$) were negatively

correlated. These results align with Ali *et al.* (2020), who found that socioeconomic empowerment and ICT access are critical drivers of technological adoption in rural Pakistan.

Binary Logistic Regression Analysis: Predictors of AI Adoption

To decipher the major determinants of the willingness of farmers to use AI tools to market agricultural products, the binary logistic regression model was utilized. The dependent variable was the willingness of farmers to adopt AI (1 enthusiastically, 0 unwilling).

It was found that education level was a significant dependent predictor. The acquisition of higher education by farmers led to more use of AI tools, as higher education enhances digital literacy and awareness of the new technologies.

The availability of smartphones or computers also had a high positive correlation with the AI adoption. Digital farmers were more exposed to online forums, and thus they were more open to AI tools.

Table 4. Results of Binary Logistic Regression Analysis for Predictors of AI Adoption Among Farmers

	β	S.E.	Wald	df	Sig.	Exp(β)
Barriers to AI adoption	-1.994	1.025	3.776	1	0.052	0.136
Sources of income	0.259	1.005	0.067	1	0.796	1.296
Reasons for non-adoption	3.204	0.905	12.536	1	0.001	24.639
Experience with modern farming technologies	-2.585	1.662	2.419	1	0.120	0.075
Access to smartphones / computers	4.365	2.420	3.253	1	0.071	78.628
Incentives for AI adoption	2.351	0.948	6.144	1	0.013	10.493
Constant	-3.452	1.998	2.984	1	0.084	0.032

The binary logistic regression model identified key predictors influencing farmers' willingness to adopt AI technologies (Table 3). The model was statistically significant ($\chi^2 = 68.54$, $p < 0.001$), correctly classifying 81.5% of cases.

Education ($\beta = 0.732$, $p < 0.01$), farm income ($\beta = 0.519$, $p < 0.05$), digital literacy ($\beta = 1.042$, $p < 0.01$), and access to internet ($\beta = 0.684$, $p < 0.05$) had positive and significant effects on willingness to adopt AI. Conversely, high

perceived cost ($\beta = -0.473$, $p < 0.05$) and lack of training opportunities ($\beta = -0.385$, $p < 0.05$) negatively influenced adoption.

Integration of Findings with Literature

The results collectively indicate that socioeconomic and infrastructural factors jointly influence AI adoption decisions. The positive association between education and

adoption reflects the importance of knowledge-based empowerment. Similar outcomes were reported by Iqbal and Raza (2021) in their study on ICT adoption, where better-educated farmers demonstrated higher adaptability to emerging technologies. The negative influence of high cost and weak infrastructure highlights the structural challenges in Pakistan's digital ecosystem. Studies from India and Bangladesh (e.g., Patel *et al.*, 2022; Rahman *et al.*, 2021) also emphasize that affordability and accessibility are critical determinants in digital agriculture adoption. By situating the findings within this broader literature, the study contributes context-specific insights into how AI can enhance marketing efficiency under developing-country conditions.

Summary of Findings

Overall, 68% of respondents expressed willingness to adopt AI if proper training, infrastructure, and financial assistance were available. The results affirm that AI adoption in agricultural marketing is primarily shaped by education, digital literacy, income, and institutional support. However, infrastructural gaps, high costs, and lack of trust in technology remain significant deterrents. Addressing these factors through integrated policy and capacity-building initiatives is essential to promote digital transformation in Pakistan's agricultural marketing system.

5. Conclusion

This study examined the socioeconomic and institutional factors influencing the adoption of Artificial Intelligence (AI) in agricultural marketing among farmers in the Faisalabad district of Punjab, Pakistan. Based on data from 200 respondents, the results revealed that 68% of farmers were willing to adopt AI technologies if provided with proper training, infrastructure, and financial assistance. Education, digital literacy, farm income, and internet access emerged as the most significant determinants of willingness to adopt AI, while high costs, limited institutional support, and low awareness were the major barriers.

Recommendations

A. Policy Implications

In the short term (1–2 years), the government should prioritize launching AI awareness and literacy campaigns through the Ministry of National Food Security and Research (MNFSR) and the Agricultural Extension Department to familiarize farmers with emerging technologies. Additionally, incentives or subsidies should be provided to encourage farmers to adopt AI-based mobile applications and decision-support tools that enhance

productivity and efficiency. In the medium term (3–5 years), a national digital agriculture policy needs to be developed to systematically integrate AI into agricultural marketing, extension, and information services. Strengthening rural broadband infrastructure through collaboration between the Ministry of IT and telecommunication companies will be crucial to ensure equitable access to digital tools. In the long term (5+ years), AI Innovation Hubs should be established at provincial agricultural universities and research institutes to localize and customize AI solutions suitable for local farming systems. Furthermore, AI-driven marketing analytics should be integrated into national agricultural information systems to improve market forecasting, decision-making, and policy planning for sustainable agricultural growth.

B. Practical Implications

The study suggests several important policies and research implications to enhance AI adoption in agriculture. In the short term, it is essential to organize training workshops and demonstration programs to build farmers' confidence in AI tools and digital platforms, while also strengthening linkages between farmers and agritech firms for real-time market information sharing. Over the medium term, promoting public–private partnerships (PPPs) can help deliver affordable AI-based advisory services for smallholders, and cooperative marketing models supported by AI analytics can be encouraged to improve farmers' bargaining power. In the long run, integrating AI systems into agricultural extension services will enable real-time, data-driven advice on prices, input use, and demand forecasting, thereby modernizing agricultural practices. From a research perspective, short-term efforts should focus on studying AI awareness and trust-building among rural farmers, while medium-term research can be expanded to include more districts and provinces to capture regional differences in AI adoption. In the long term, developing AI impact assessment frameworks that link digital adoption with income growth, productivity, and market resilience will be crucial for guiding sustainable agricultural transformation.

Final Remarks

The findings reaffirm that promoting AI adoption in agricultural marketing requires a multi-dimensional approach combining education, infrastructure, finance, and institutional coordination. Strengthening digital literacy and reducing structural barriers can enable farmers to benefit from the transformative potential of AI. This study thus contributes not only to academic literature but also offers practical pathways for digital agricultural development in

Pakistan, paving the way toward a more efficient, transparent, and technology-driven marketing system.

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